UNCLASSIFIED
SECRET

Copy 1
RM E56I19a

NACA RM E56I19a

3 1176 00112 2663

CLASSIFICATION CHANGED
NACA
...D. MEMO
...d. Haines,
by Blw 3-7-72

RESEARCH MEMORANDUM

ANALYSIS OF TURBOJET AND RAM-JET ENGINE CYCLES USING VARIOUS FUELS

By E. Clinton Wilcox, Richard J. Weber, and Leonard K. Tower

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFICATION CHANGED
TO CONFIDENTIAL
By authority of NASA Publication Announcement #2 Nov. 12, 1958
JBE
I.N. 10,756
Copy 1

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

DEC 3 1956

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

November 27, 1956

UNCLASSIFIED
SECRET

NACA LIBRARY
LANGLEY AERONAUTICAL LABORATORY
Langley Field, Va.

CONFIDENTIAL

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

CLASSIFICATION CHANGED
TO UNCLASSIFIED
BY AUTHORITY OF NASA HDQ. MEMO
DTD 9-27-71, S/H. G. Maines,
BY Blm 3-7-72

RESEARCH MEMORANDUM

ANALYSIS OF TURBOJET AND RAM-JET ENGINE CYCLES USING VARIOUS FUELS

By E. Clinton Wilcox, Richard J. Weber,
and Leonard K. Tower

SUMMARY

Except for rough approximations, it appears necessary to account for variations in combustion-gas properties when different fuels are applied in turbojet and ram-jet cycle calculations. Representative cycle performance is presented using hydrogen, pentaborane, ethylene decaborane, and a conventional hydrocarbon fuel. Turbojet performance is given up to a flight Mach number of 3.0, both with and without afterburning. Ram-jet performance is given up to a Mach number of 4.0. When compared with the hydrocarbon fuel, the thrust per pound of airflow and engine over-all efficiency, with other fuels, may be either higher or lower depending on the operating conditions. Differences of as much as 10 percent or more are found in some cases.

CJ-1

INTRODUCTION

The use of high-energy fuels in aircraft propulsion systems is currently receiving much attention because of the possibilities they provide for decreased fuel consumption and increased altitude capability. Rough estimates of engine performance using various fuels usually assume that the thrust is independent of the fuel type and the specific fuel consumption is inversely proportional to the heating value. This corresponds to assuming a constant engine over-all efficiency (where over-all efficiency is defined as the net propulsive work produced by the engine divided by the heat content of the fuel used). In some cases, however, the changes in exhaust-gas properties and mass addition with various fuels may result in significant differences in thrust and over-all efficiency, which should be considered in more precise studies.

In the course of several projects recently conducted at the NACA Lewis laboratory, a number of engine cycle calculations using various fuels was made. These data have been collected for presentation in this report to illustrate the performance of turbojet and ram-jet cycles

UNCLASSIFIED
SECRET
CONFIDENTIAL
I.N. 10,756
DEC 3 1956
NACA LIBRARY
LANGLEY AERONAUTICAL LABORATORY
Langley Field, Va.

utilizing several of the more promising high-energy fuels. Results are presented in terms of engine over-all efficiency and thrust per pound of airflow as functions of flight Mach number. Effects of fuel type on flow areas, turbine operation, and so forth, are not included.

The fuels considered are hydrogen, pentaborane, and ethylene decaborane. A conventional hydrocarbon fuel, CH_2, being representative of the JP-4 and JP-5 jet fuels, is also included for comparison.

Turbojet cycles were calculated with these fuels for Mach numbers up to 3.0, both nonafterburning and with afterburning to 3500° R. Several compressor pressure ratios and turbine-inlet temperatures were considered. Ram-jet cycles were calculated up to a Mach number of 4.0, with combustion temperatures from 1500° to 4000° R. Calculations assuming both frozen and equilibrium expansion were made to investigate the importance of B_2O_3-phase changes for the boron-containing fuels.

SYMBOLS

F/w_a	engine thrust per pound of airflow, lb/(lb/sec)
f	fuel-air ratio
g	acceleration due to gravity, 32.174 ft/sec^2
H	lower heating value of fuel, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu
M	Mach number
sfc	specific fuel consumption, (lb/hr)/lb
V	velocity, ft/sec
η	over-all efficiency

Subscripts:

e	nozzle exit
0	free stream

[redacted]

ANALYSIS

The engine cycle analyses were carried out by computing the change in state of the working fluid in passing through the various engine components. The required thermodynamic gas properties were taken from the tables of reference 1. The effects of chemical dissociation were neglected. However, account was taken of the vaporization of the solid B_2O_3 present in the combustion products of the fuels containing boron.

Cycle thrust per pound of airflow and over-all efficiency are defined by the following expressions:

$$\frac{F}{w_a} = \frac{1}{g}\left[(1 + f)V_e - V_0\right] \tag{1}$$

$$\eta = \frac{\text{Work out}}{\text{Energy in}} = \frac{\frac{F}{w_a} V_0}{fJH} = \frac{4.63\ V_0}{(sfc)H} \tag{2}$$

The nozzle-exit velocity term V_e appearing in the equation for cycle thrust per pound of airflow F/w_a is the product of the nozzle thrust coefficient and the ideal completely expanded jet velocity.

In the calculations it was assumed that the use of the high-energy fuels did not alter the performance of the various engine components. For example, the possibility of a deleterious effect of solid combustion products on turbine performance was ignored. Also, the same combustion efficiency was assumed for all fuels, although the high-energy fuels are expected to be better in this regard at high-altitude conditions than the conventional hydrocarbons.

The lower heating values used for the various fuels are as follows:

Fuel	Lower heating value, H, Btu/lb
Hydrocarbon, CH_2	18,700
Hydrogen, H_2	51,570
Pentaborane, B_5H_9	29,160
Ethylene decaborane, $B_{10}H_{13}C_2H_5$	26,460

[redacted]

The heating value assumed for ethylene decaborane is that for the pure substance; presently available commercial grades of this fuel (EDB) have exhibited values of something less than 25,000 Btu per pound.

In most cases considered, the same fuel was used in both the primary combustor and the afterburner of the turbojet. One case was investigated, however, in which hydrocarbon fuel was used in the primary combustor and pentaborane in the afterburner. For this case the average heating value can be found from the following expression:

$$H = \frac{f_{HC}H_{HC} + f_{P}H_{P}}{f_{HC} + f_{P}} \qquad (3)$$

where the subscripts HC and P refer to hydrocarbon and pentaborane, respectively.

The data presented apply for any altitude in the stratosphere for fuels that do not contain boron. There is an altitude effect, however, on cycle-performance with boron-containing fuels. One of the combustion products is B_2O_3, which is a solid at room temperature. At the higher temperatures considered in the combustion chamber, the B_2O_3 that is formed tends to vaporize. This vaporization is encouraged both by higher combustion temperatures and by lower combustion pressures. The thermal energy absorbed during vaporization is not available for producing thrust and may be interpreted as a decrease in effective heating value. Most of the calculations were made for an altitude of 40,000 feet. Several other altitudes were considered for the pentaborane-fueled ram jet in order to investigate the importance of this altitude effect.

As the combustion products are expanded in the exhaust nozzle, the resulting temperature drop tends to condense the vaporized B_2O_3, and the heat of condensation is made partially available for producing thrust (equilibrium expansion). Inasmuch as the gas velocity through the nozzle is very high, however, insufficient time may be available in some cases for the B_2O_3 to condense, and the B_2O_3 remains in the phase in which it left the combustion chamber (frozen expansion). For the boron fuels, therefore, performance for both equilibrium and frozen expansion was investigated.

The important component assumptions made for the two engine types were as follows.

Turbojet Assumptions

Inlet. - The inlet-diffuser pressure recovery was scheduled with flight Mach number as shown in figure 1. These values are representative of a diffuser having two oblique shocks and one normal shock.

Compressor. - The compressor adiabatic efficiency was taken as 0.85 for all cases. The actual pressure ratio of a given compressor deviates from the rated (i.e., sea-level static) value as the flight conditions are changed. The variation of operating compressor pressure ratio with flight Mach number is shown in figure 2 for several values of rated pressure ratio. The illustrated variations are based on the assumptions of flight in the stratosphere, constant mechanical speed, choked turbine nozzles, and a typical variation of equivalent airflow with equivalent compressor speed. A given value of rated compressor pressure ratio corresponds to a specific engine design, and changes in rated compressor pressure ratio would require a completely redesigned engine. For hydrocarbon and hydrogen fuels, rated compressor pressure ratios of 4, 8, and 12 were considered over the entire flight Mach number range. For the boron-containing fuels, only one rated pressure ratio was considered at each flight Mach number as given in the following table:

Flight Mach number	Rated pressure ratio
1.0	12
1.5	12
2.0	8
2.5	4
3.0	4

These selected rated pressure ratios represent a compromise between maximum thrust and over-all efficiency. The corresponding compressor operating pressure ratios may be obtained from figure 2.

Primary combustor. - The combustion efficiency (ratio of ideal to actual fuel-air ratios) was taken as 0.95. The ratio of combustor-exit to -inlet total pressure was assumed to be 0.95.

Turbine. - An adiabatic efficiency of 0.90 was assumed.

Afterburner. - The combustion efficiency was assumed to be 0.90. A loss of 0.05 in total-pressure ratio across the afterburner was assumed to account for both friction and momentum pressure loss.

[redacted]

Exhaust nozzle. - The nozzle thrust coefficient (ratio of actual thrust to ideal thrust if completely expanded to ambient pressure) was taken as 0.96.

Ram-Jet Assumptions

Inlet. - The same inlet characteristics were assumed as for the turbojet.

Combustor. - Combustor-inlet Mach number was taken as 0.175. A combustion efficiency of 0.90 was assumed, with a flameholder drag of twice the incompressible dynamic head. A further momentum pressure loss due to heat addition was included.

Exhaust nozzle. - The same exhaust-nozzle characteristics were assumed as for the turbojet.

RESULTS AND DISCUSSION

Turbojet Performance

Performance of turbojet cycles using hydrocarbon fuel is shown in figures 3 and 4; performance using hydrogen is shown in figures 5 and 6. Thrust per pound of airflow and engine over-all efficiency are plotted against flight Mach number for several rated compressor pressure ratios. Figures 3 and 5 are for the nonafterburning case, and figures 4 and 6 are for afterburning to a temperature of 3500° R. Parts (a), (b), and (c) are for turbine-inlet temperatures of 2000°, 2500°, and 3000° R, respectively.

Performance of the afterburning turbojet cycle utilizing a hydrocarbon fuel in the primary combustor and pentaborane in the afterburner is shown in figure 7. Interest in this case stems largely from possible adverse effects of boron oxide deposition on turbine performance. Thrust per pound of airflow and engine over-all efficiency are shown in figure 7(a) for equilibrium expansion in the exhaust nozzle, that is, assuming that any vaporized B_2O_3 in the afterburner has sufficient time to condense during expansion. Figure 7(b) presents similar data for frozen expansion in the exhaust nozzle. It was assumed that the composition was in equilibrium at the combustion-chamber-outlet conditions and that the relative proportions of vaporized and condensed B_2O_3 did not change during expansion. The required primary and afterburner fuel-air ratios shown in figure 7(c) apply to both equilibrium and frozen expansion. Comparison of figures 7(a) and (b) indicates that, for the altitude considered (40,000 ft), both equilibrium and frozen expansion yield about

the same performance. This would not necessarily be the case for other altitudes. This effect is more completely considered in a subsequent discussion of a pentaborane-fueled ram jet.

Afterburning and nonafterburning turbojet cycle performance for two turbine-inlet temperatures is shown in figures 8 and 9 for pentaborane and ethylene decaborane fuels, respectively. The case of equilibrium nozzle expansion is given in part (a) and frozen expansion in part (b). The equilibrium and frozen expansion refers only to the exhaust nozzle, because neither primary-combustor temperature is high enough to vaporize any significant portion of the B_2O_3 entering the turbine.

The effect of fuel type on turbojet cycle performance is summarized in figure 10 at a turbine-inlet temperature of 2500° R. Rated compressor pressure ratio is varied with flight Mach number for all the fuels according to the table in the ANALYSIS. Equilibrium expansion in the exhaust nozzle is assumed for the boron-containing fuels. For all fuel types the thrust per pound of airflow decreases approximately linearly with increasing Mach number. For the afterburning case, engine over-all efficiency increases nearly linearly with Mach number in the range considered. For the nonafterburning case, engine over-all efficiency tends to level off at the higher Mach numbers.

Variations in thrust per pound of airflow and engine over-all efficiency of as much as 10 percent are observed when different fuels are used. These variations result from changes in mass addition, specific heat, and gas constant for the combustion products. The magnitude of the differences and even the comparative rank of the fuels vary with the engine operating conditions. In general, hydrogen fuel appears to provide somewhat improved thrust per pound of airflow and approximately equal over-all efficiency when compared with a hydrocarbon fuel. Performance using the boron-containing fuels appears similar to or slightly inferior to that with the hydrocarbon fuel. The assumption of frozen nozzle expansion would tend to worsen their performance still further. Of course, these differences in engine over-all efficiency for the various fuels, though significant, are small compared with the differences in heating value.

The effect of changes in rated compressor pressure ratio is shown in figure 11 for a flight Mach number of 3.0. Data are given for both hydrogen and hydrocarbon fuels. Parts (a) and (b) show nonafterburning performance for turbine-inlet temperatures of 2000° and 3000° R, respectively; part (c) is for a turbine-inlet temperature of 2000° R, with afterburning to 3500° R. For the nonafterburning cycle, maximum over-all efficiency with both fuels occurs at higher pressure ratios than those for maximum thrust. For the afterburning cycle, both the thrust per pound of airflow and the over-all efficiency are relatively insensitive to changes in pressure ratio for both fuels.

[redacted]

Ram-Jet Performance

Thrust per pound of airflow and over-all efficiency for the ram-jet cycle are presented in figures 12 and 13 for hydrocarbon and hydrogen fuel, respectively. Data for pentaborane fuel are given in figures 14 and 15, based on assumptions of equilibrium and frozen expansion in the exhaust nozzle, respectively. Parts (a), (b), and (c) of figures 14 and 15 are for altitudes of 40,000, 60,000, and 80,000 feet, respectively. Similar performance for ethylene decaborane is shown in figure 16 at an altitude of 40,000 feet, where part (a) is for equilibrium expansion and part (b) for frozen expansion.

Comparison of the various fuels over a range of Mach numbers is made in figure 17(a) for a combustion temperature of 4000° R. For all the fuels, maximum thrust per pound of airflow occurs at a Mach number of approximately 2.75. Engine over-all efficiency rises rapidly with Mach number without reaching a maximum in the range considered. As was the case for the turbojet cycle, significant differences in both thrust and efficiency occur with the use of different fuels because of changes in the properties of the combustion products. No fuel appears to be superior in both thrust and efficiency, and the calculated differences vary with the flight conditions.

The effect of changes in combustion temperature is shown in figure 17(b) for a flight Mach number of 4.0. Figure 17(b) differs from the previously discussed figures in that engine over-all efficiency is shown as a function of thrust per pound of airflow for each of the fuels considered. The relative superiority of one fuel over another is seen to depend both on the combustion temperature and on whether the thrust per pound of airflow or the over-all efficiency is taken as the criterion of merit.

The data for the boron-containing fuels given in figure 17 is for equilibrium expansion in the exhaust nozzle and an altitude of 40,000 feet.

In figure 18 the effect of altitude on the performance of a pentaborane-fueled ram jet is shown. For a combustion temperature of 2000° R, there is no altitude effect and the same result is obtained for both frozen and equilibrium expansion. This is because only a negligible part of the B_2O_3 is vaporized at this temperature. Appreciable amounts of B_2O_3 are vaporized in the combustor, however, for a combustion temperature of 4000° R. Increasing altitude increases the amount of vaporization and lowers the over-all engine efficiency. The recovery of some of the heat of vaporization during equilibrium expansion in the nozzle produces higher efficiency and thrust than in the case of frozen expansion. The decreased pressure accompanying increased altitudes results in more

[redacted]

vaporized B_2O_3; and, hence, the amount of fuel necessary to obtain a given combustion-chamber temperature increases. This increased fuel addition may in some cases result in an increased thrust per pound of airflow at increased altitudes, although at the expense of decreased efficiency. This effect is illustrated by the data presented in figure 18 for equilibrium expansion and a combustion-chamber temperature of 4000° R.

CONCLUDING REMARKS

A theoretical analysis of the performance of the turbojet and ramjet cycles using various fuels indicated that, except for rough approximations, it is necessary to consider the effects of variation in combustion-gas properties and fuel mass addition when computing cycle performance. Differences in thrust per pound of airflow and engine over-all efficiency of 10 percent or more may exist because of these effects.

In general, the use of hydrogen fuel resulted in a somewhat increased thrust per pound of airflow and a slightly decreased engine over-all efficiency when compared with a conventional hydrocarbon fuel. The boron-containing fuels were inferior in both thrust per pound of airflow and engine over-all efficiency when compared with a conventional hydrocarbon fuel. The differences in performance obtained using the various fuels were influenced by the engine operating conditions.

For the boron-containing fuels at high combustion-chamber temperatures, equilibrium expansion in the exhaust nozzle gives a greater thrust per pound of airflow and engine over-all efficiency than frozen expansion. The difference between equilibrium and frozen expansion increases as the flight altitude increases. At low combustion-chamber temperatures, equilibrium and frozen expansion give the same performance and there is no appreciable altitude effect.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 26, 1956

REFERENCES

1. Hall, Eldon W., and Weber, Richard J.: Tables and Charts for Thermodynamic Calculations Involving Air and Fuels Containing Boron, Carbon, Hydrogen, and Oxygen. NACA RM E56B27, 1956.

CJ-2

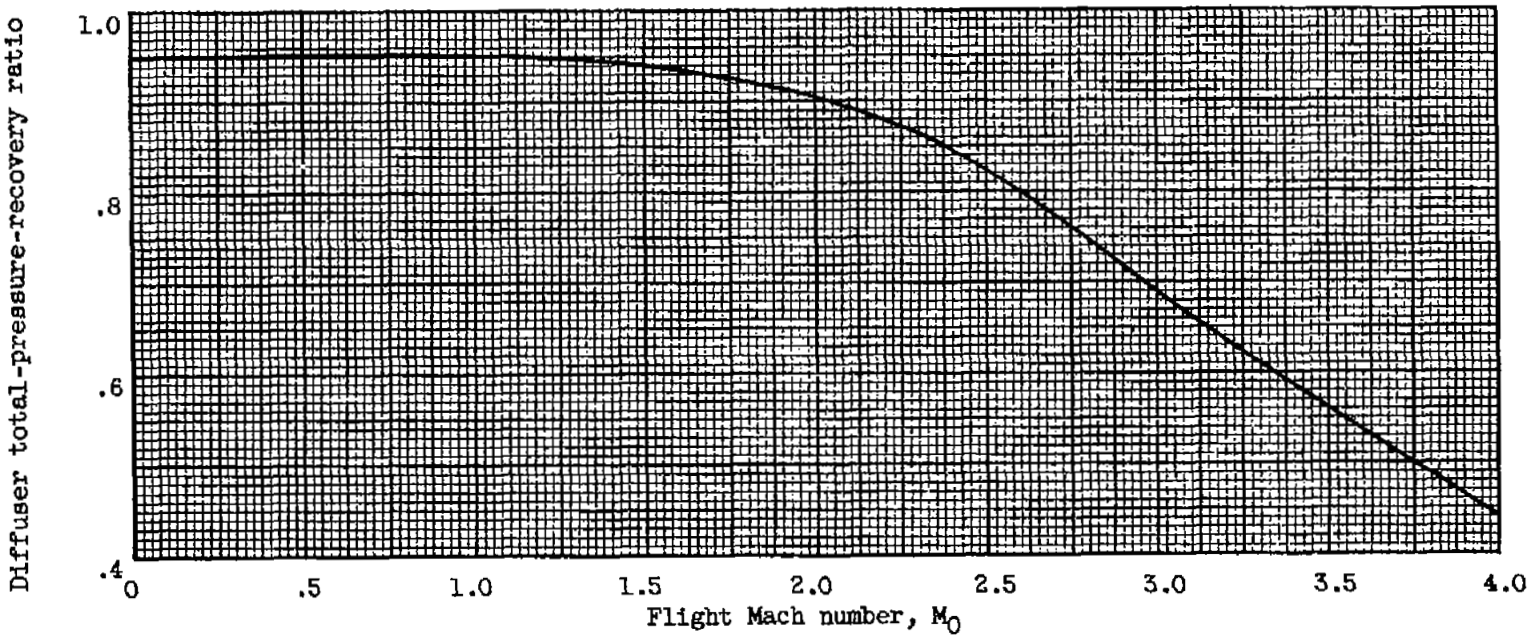


Figure 1. - Assumed diffuser pressure recoveries at various flight Mach numbers.

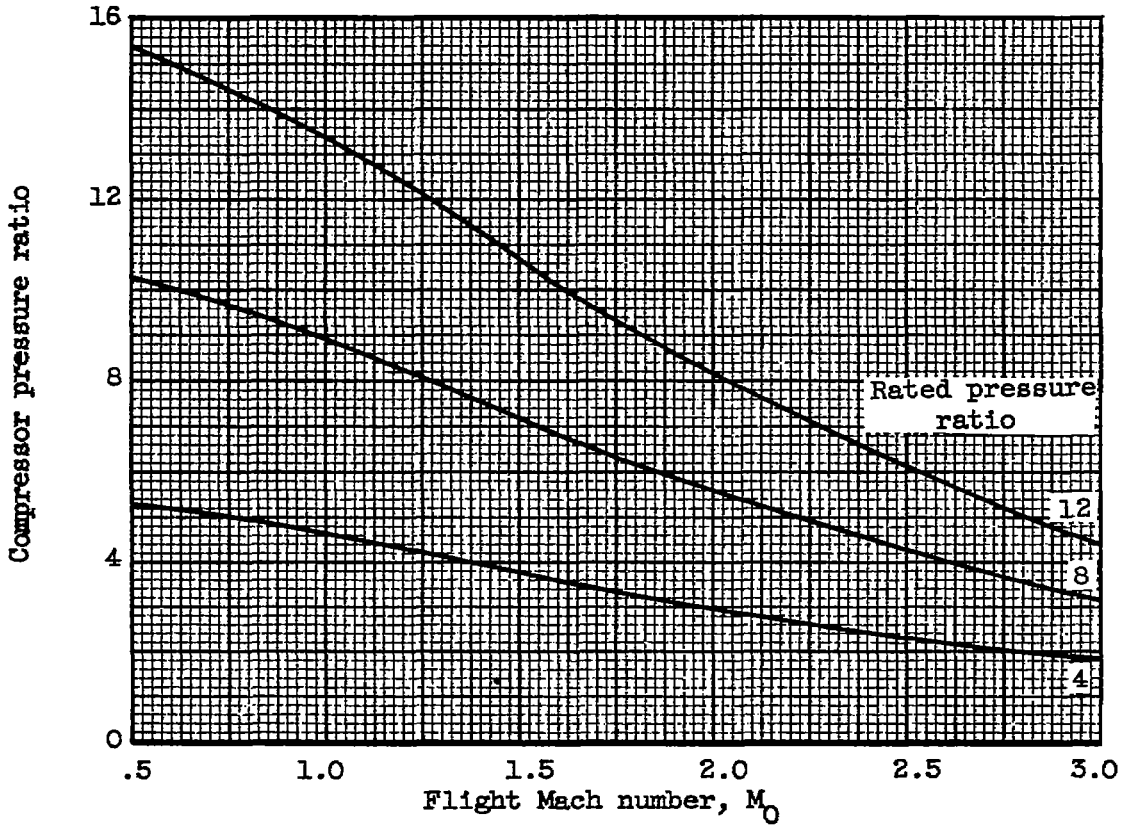
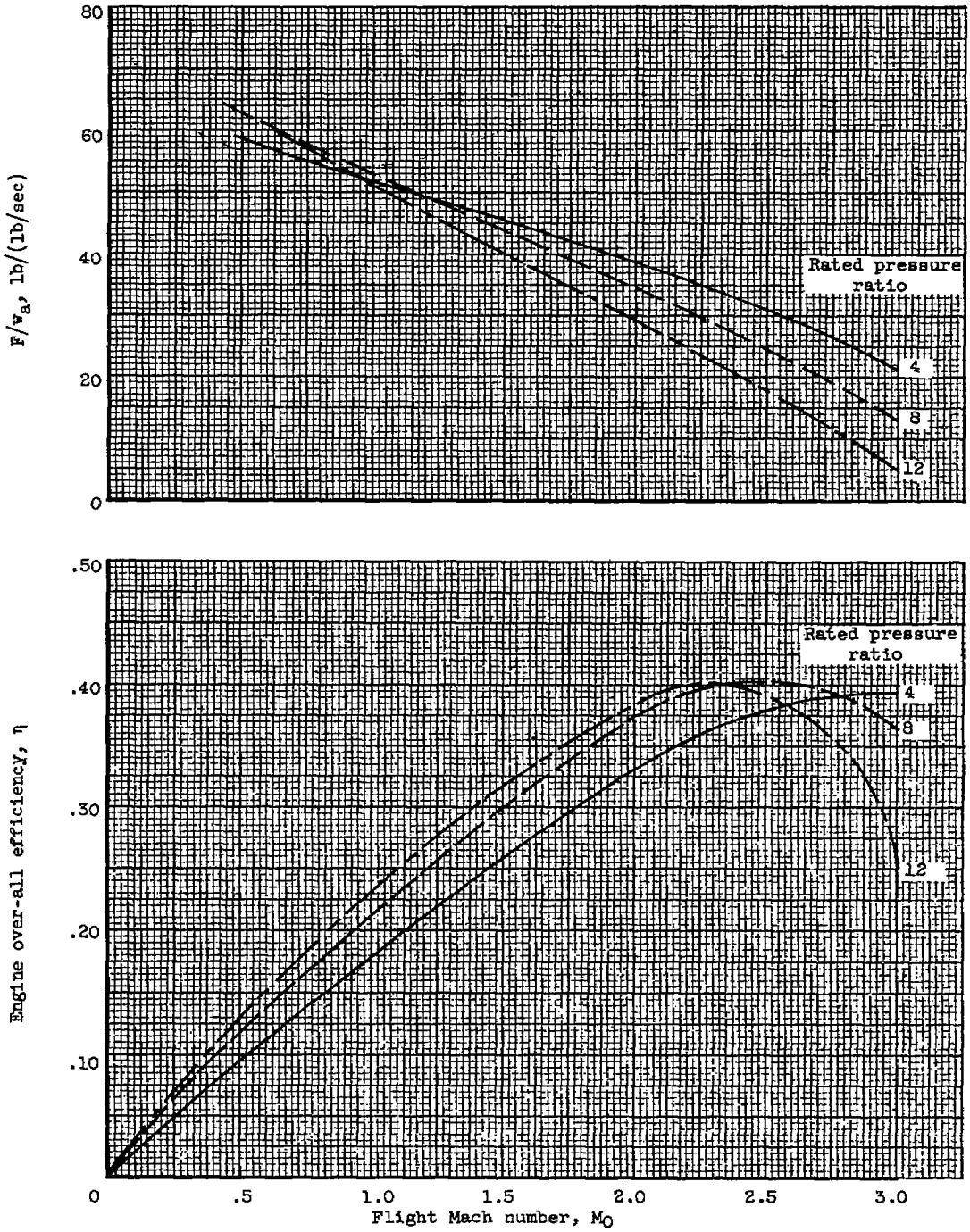


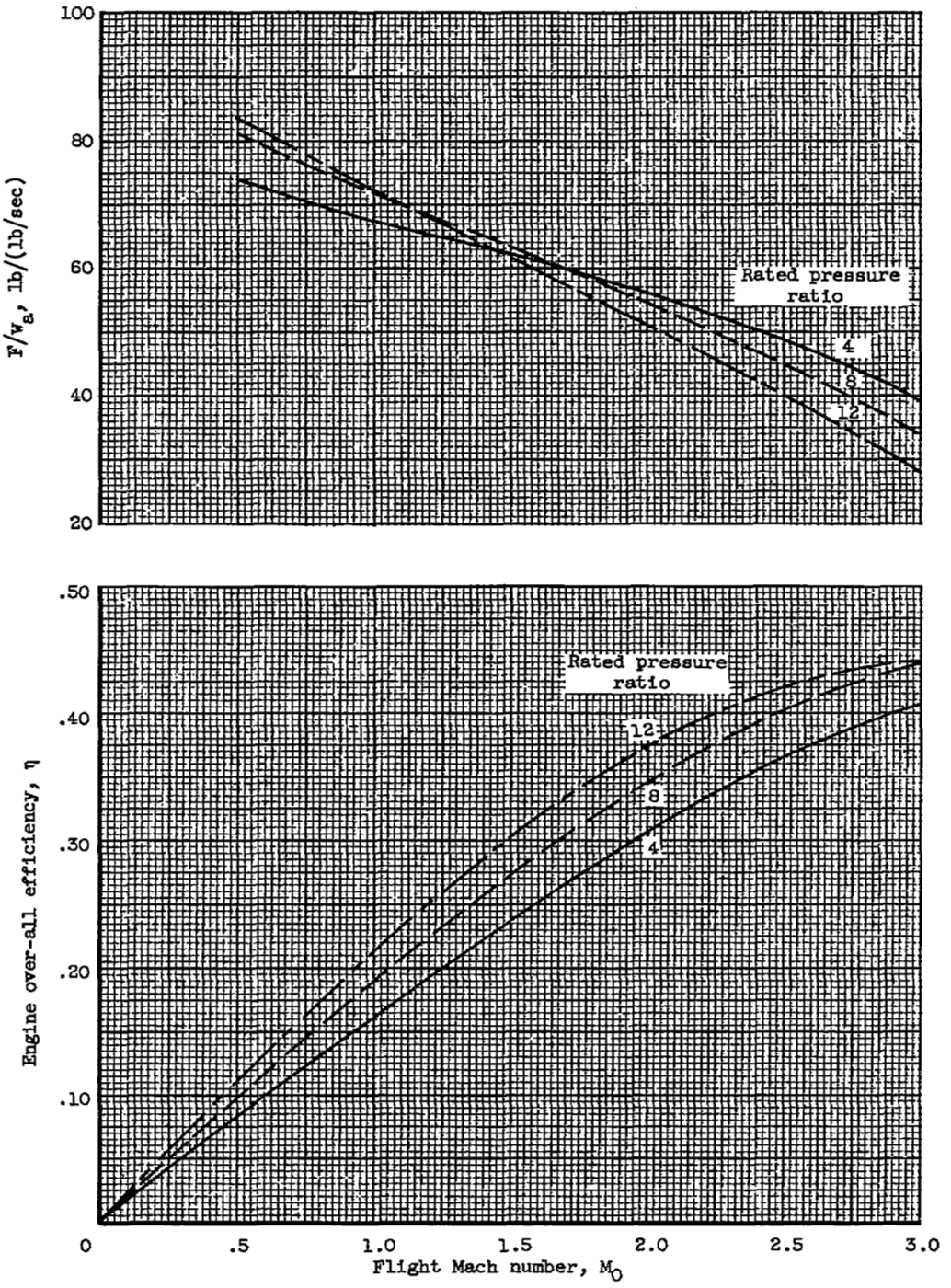
Figure 2. - Variation in compressor operating pressure ratio with flight Mach number. Altitude, stratosphere.

CJ-2 back



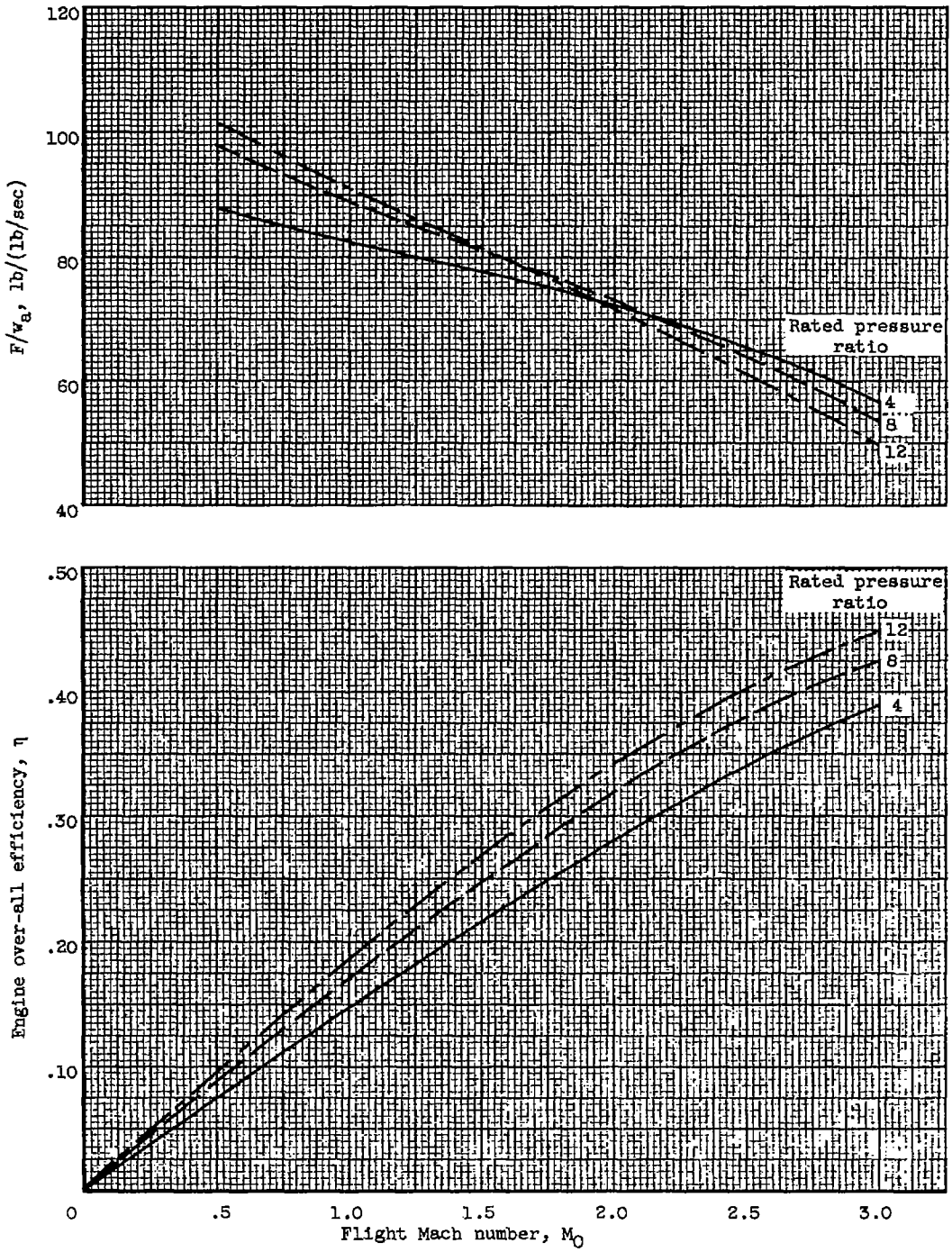
(a) Turbine-inlet temperature, 2000° R.

Figure 3. - Turbojet cycle performance with hydrocarbon fuel (no afterburner).



(b) Turbine-inlet temperature, 2500° R.

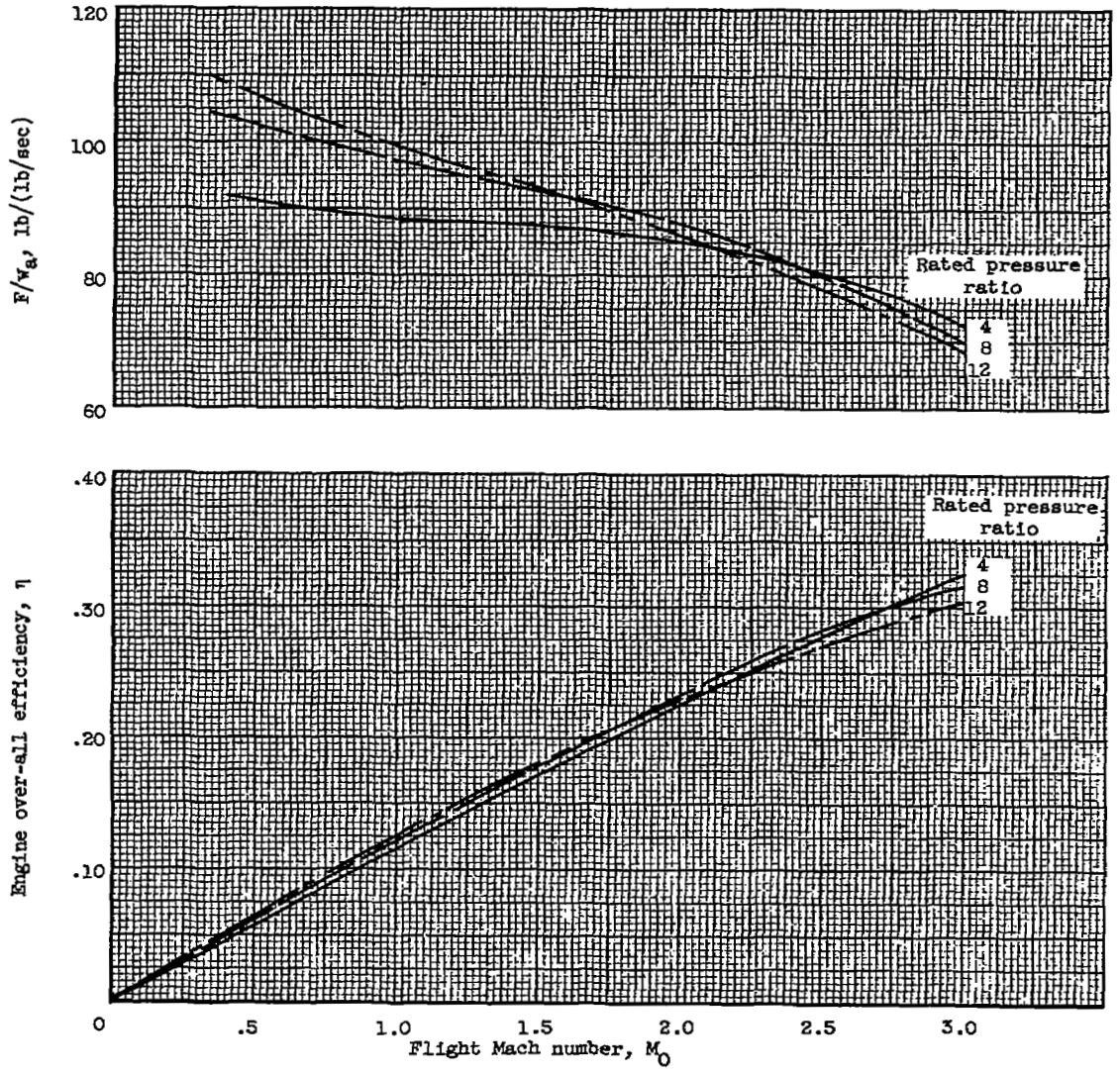
Figure 3. - Continued. Turbojet cycle performance with hydrocarbon fuel (no afterburner).



(c) Turbine-inlet temperature, 3000° R.

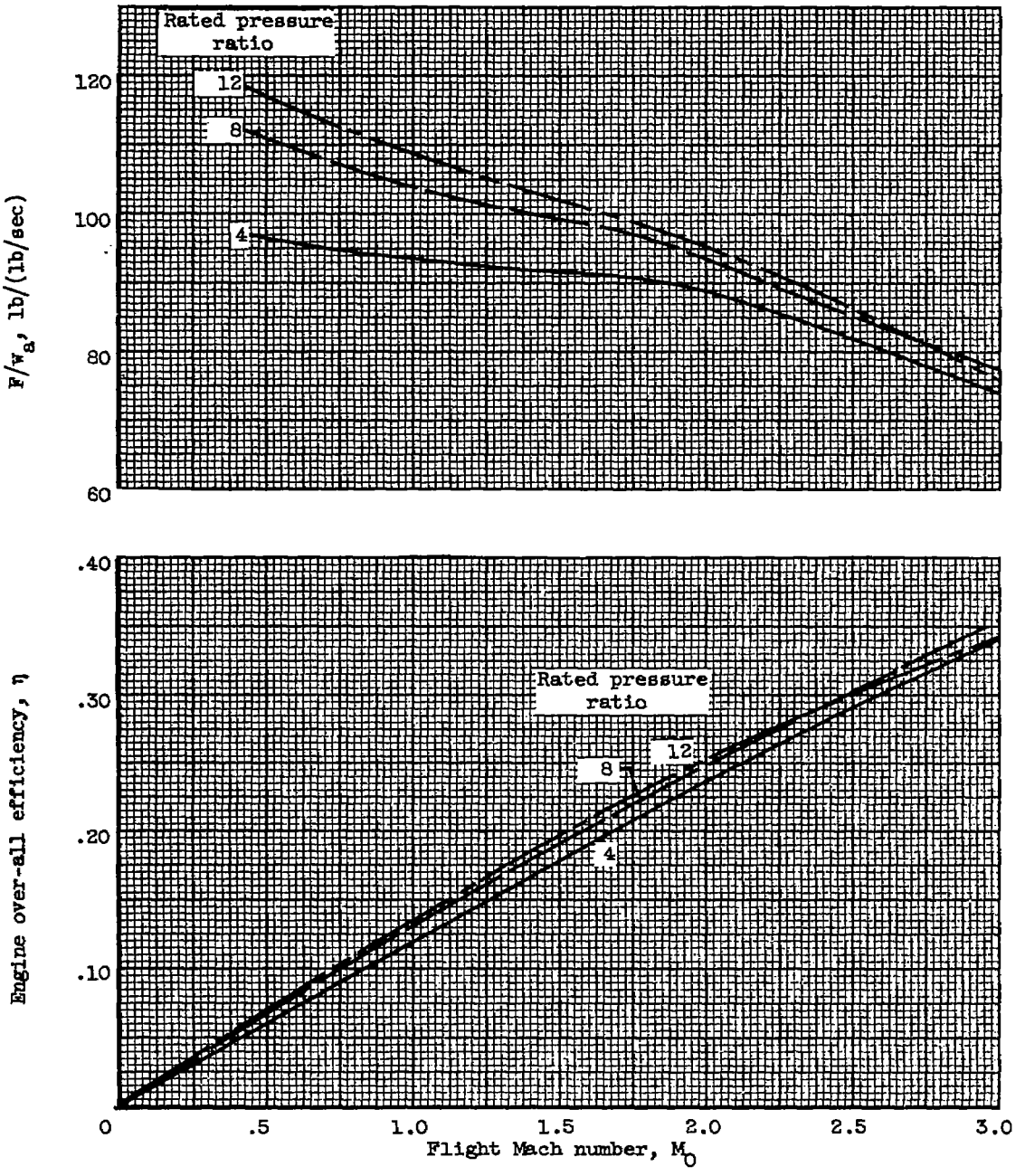
Figure 3. - Concluded. Turbojet cycle performance with hydrocarbon fuel (no afterburner).

[redacted]



(a) Turbine-inlet temperature, 2000° R.

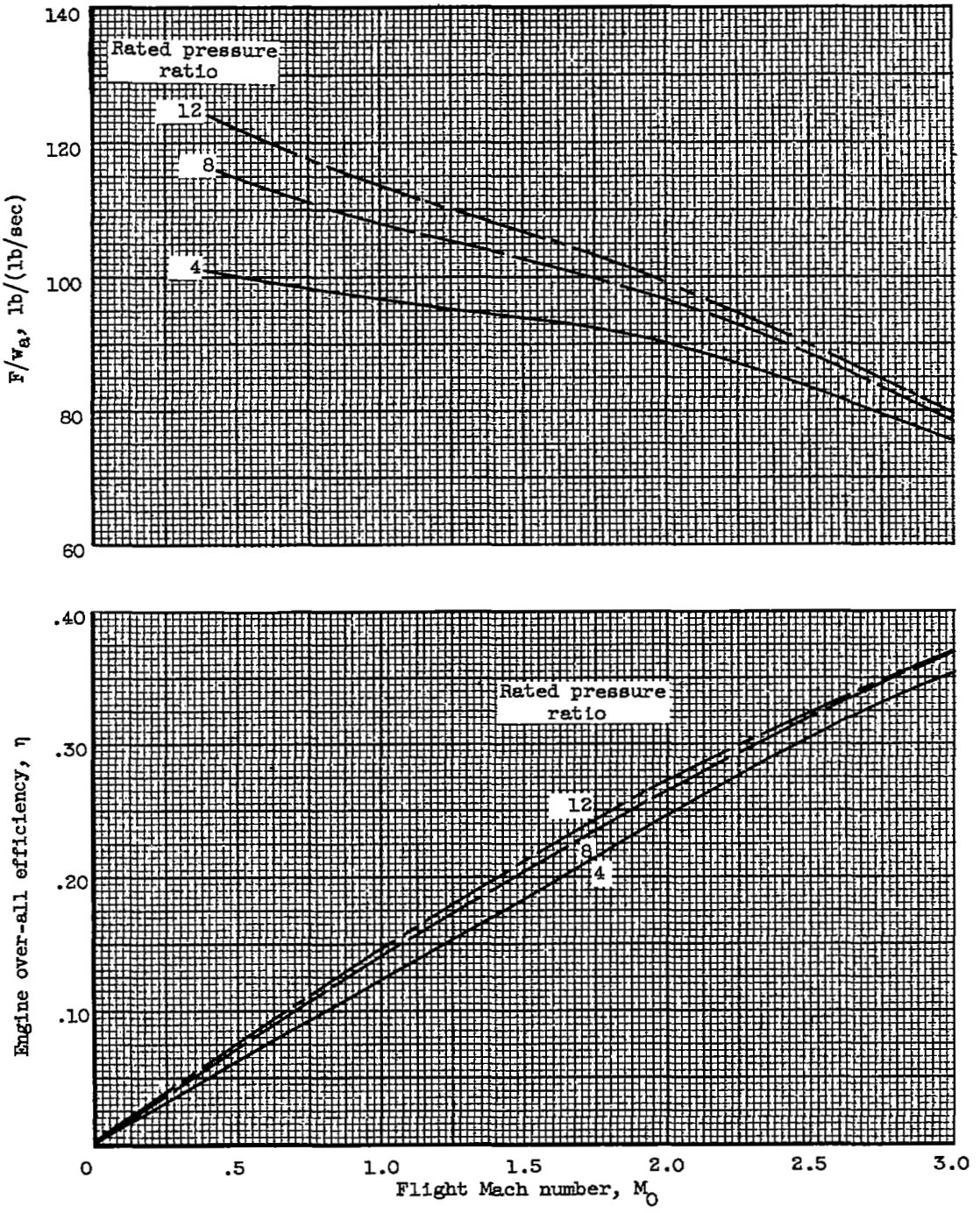
Figure 4. - Turbojet cycle performance with hydrocarbon fuel. Afterburner temperature, 3500° R.



(b) Turbine-inlet temperature, 2500° R.

Figure 4. - Continued. Turbojet cycle performance with hydrocarbon fuel. Afterburner temperature, 3500° R.

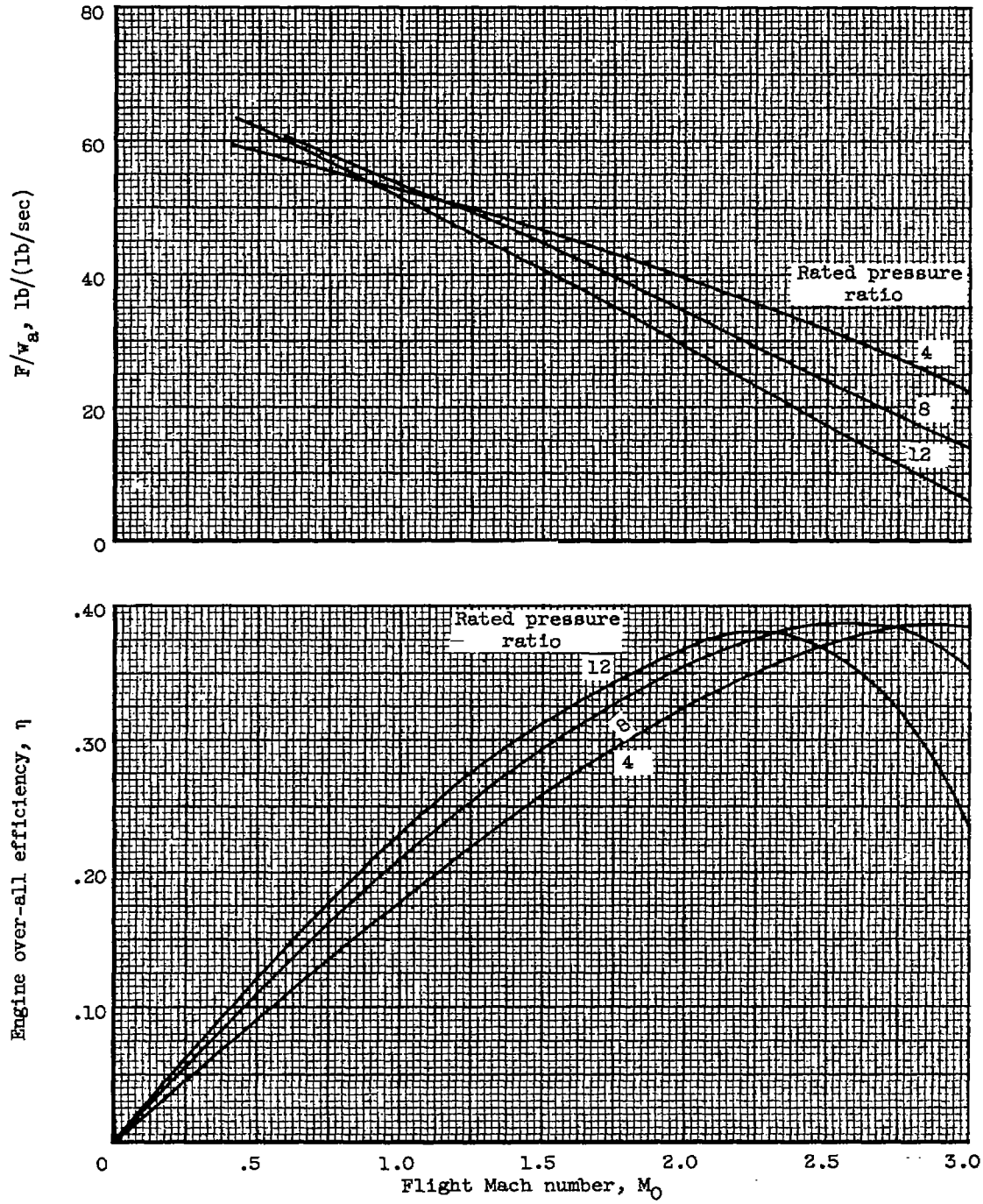
[redacted]



(c) Turbine-inlet temperature, 3000° R.

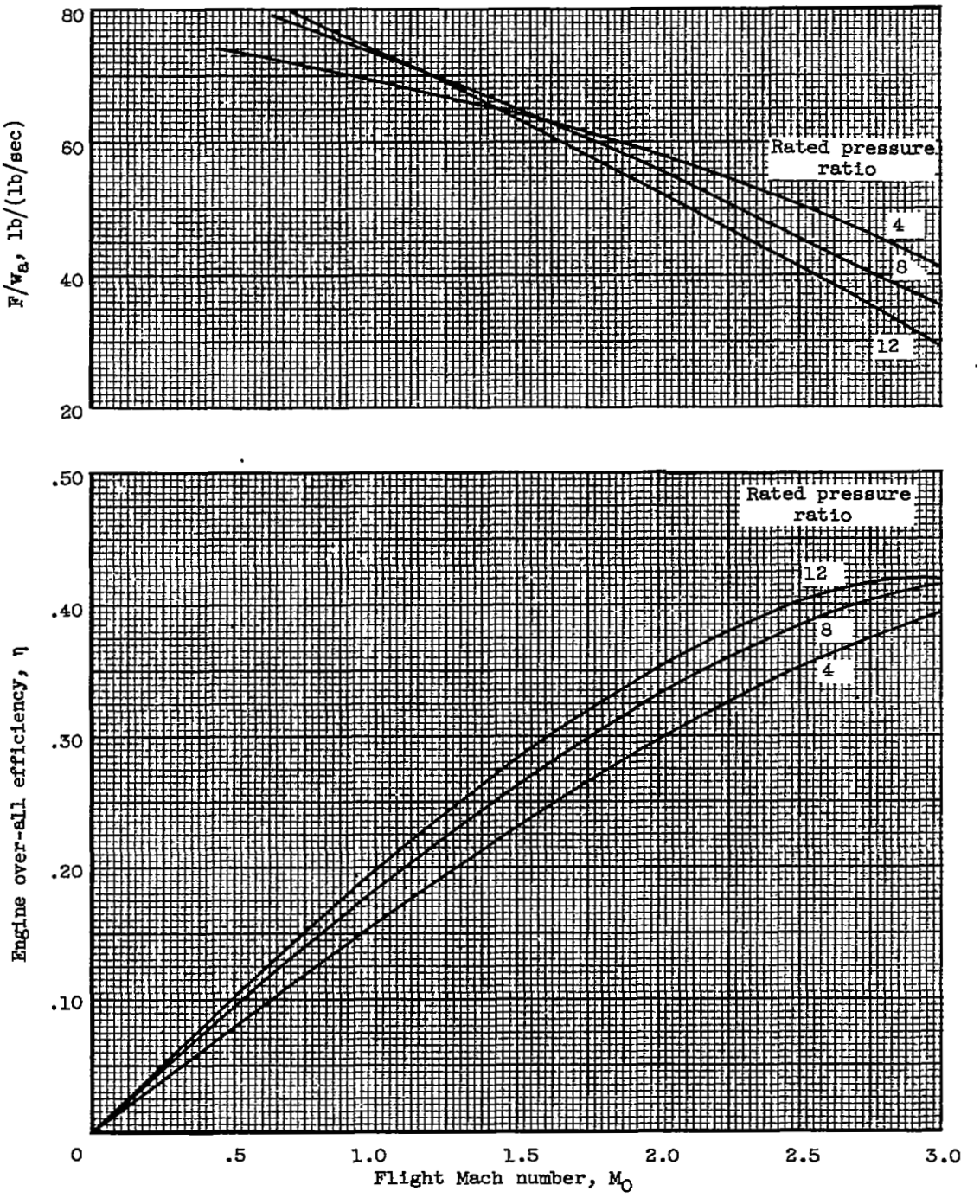
Figure 4. - Concluded. Turbojet cycle performance with hydrocarbon fuel. Afterburner temperature, 3500° R.

CJ-3



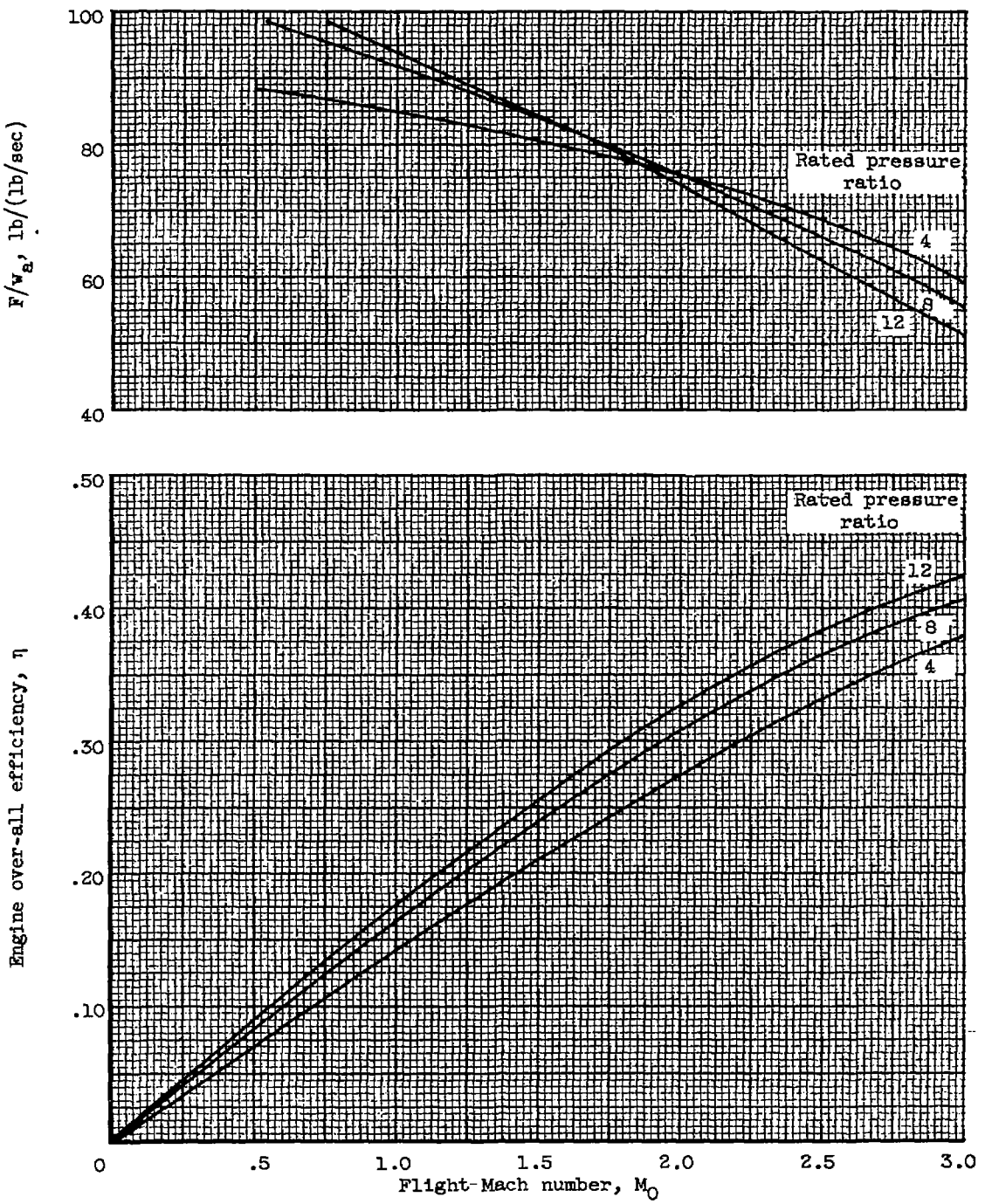
(a) Turbine-inlet temperature, 2000° R.

Figure 5. - Turbojet cycle performance with hydrogen fuel (no afterburner).



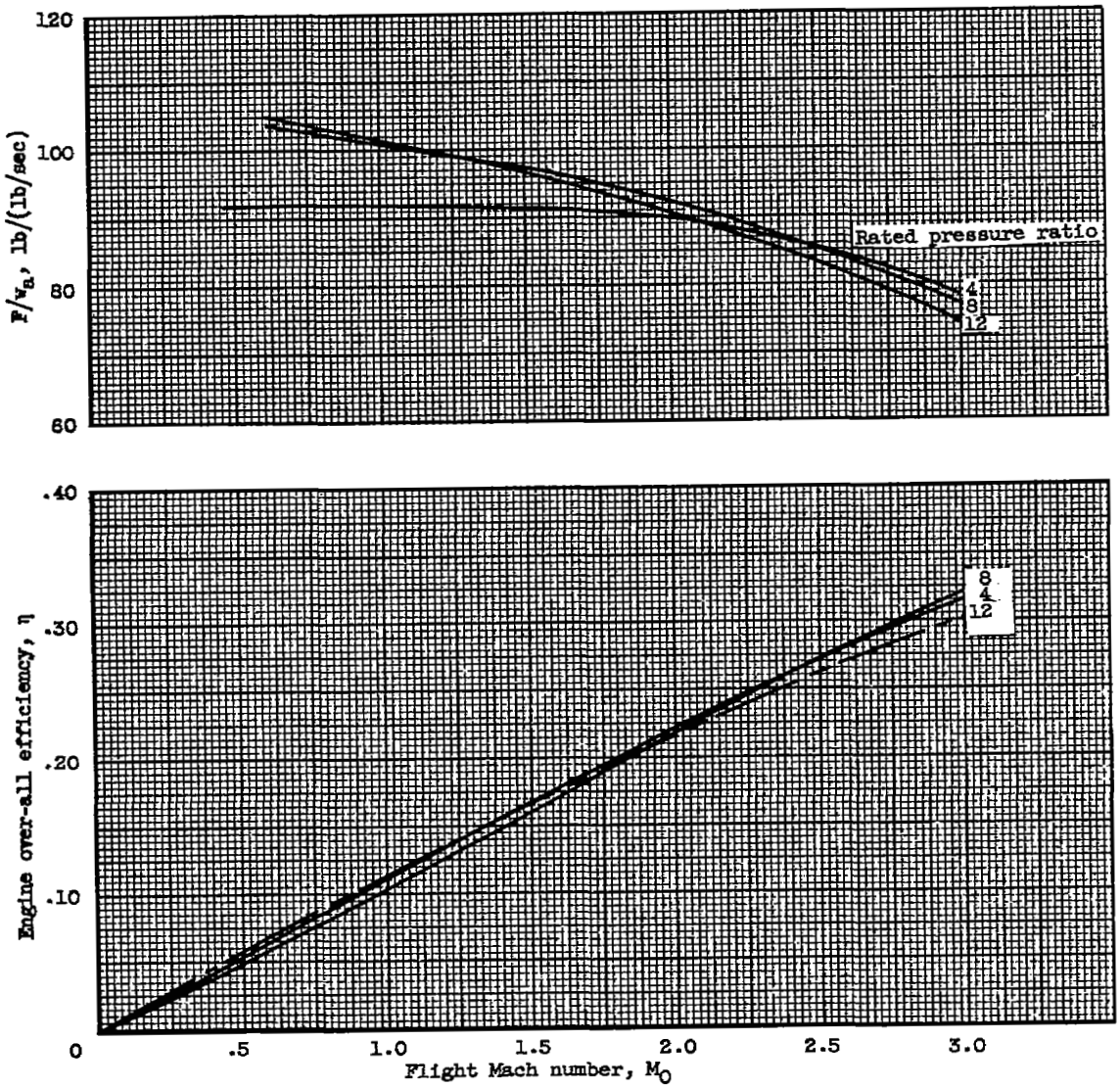
(b) Turbine-inlet temperature, 2500° R.

Figure 5. - Continued. Turbojet cycle performance with hydrogen fuel (no afterburner).



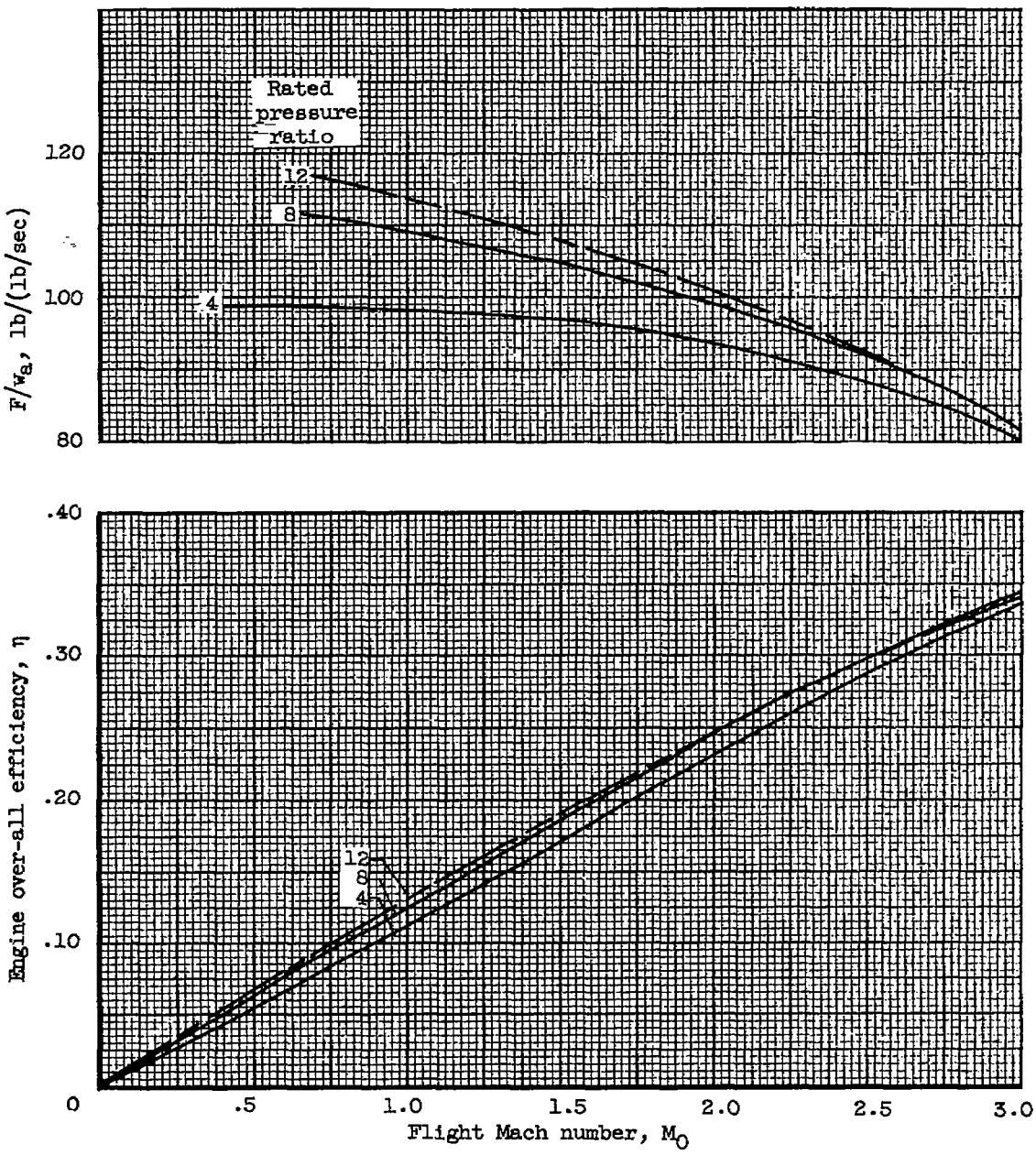
(c) Turbine-inlet temperature, 3000° R.

Figure 5. - Concluded. Turbojet cycle performance with hydrogen fuel (no afterburner).



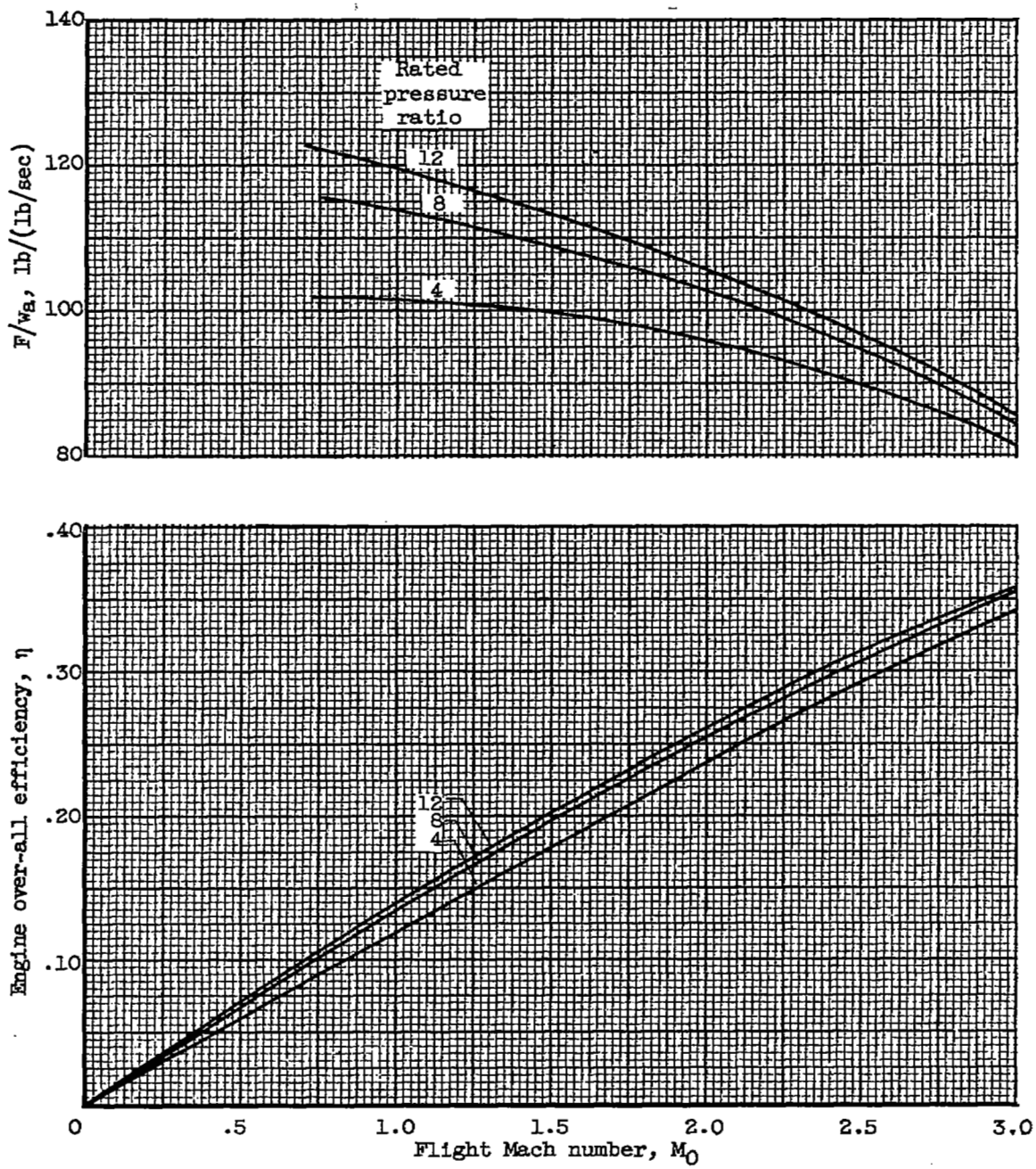
(a) Turbine-inlet temperature, 2000° R.

Figure 6. - Turbojet cycle performance with hydrogen fuel. Afterburner temperature, 3500° R.



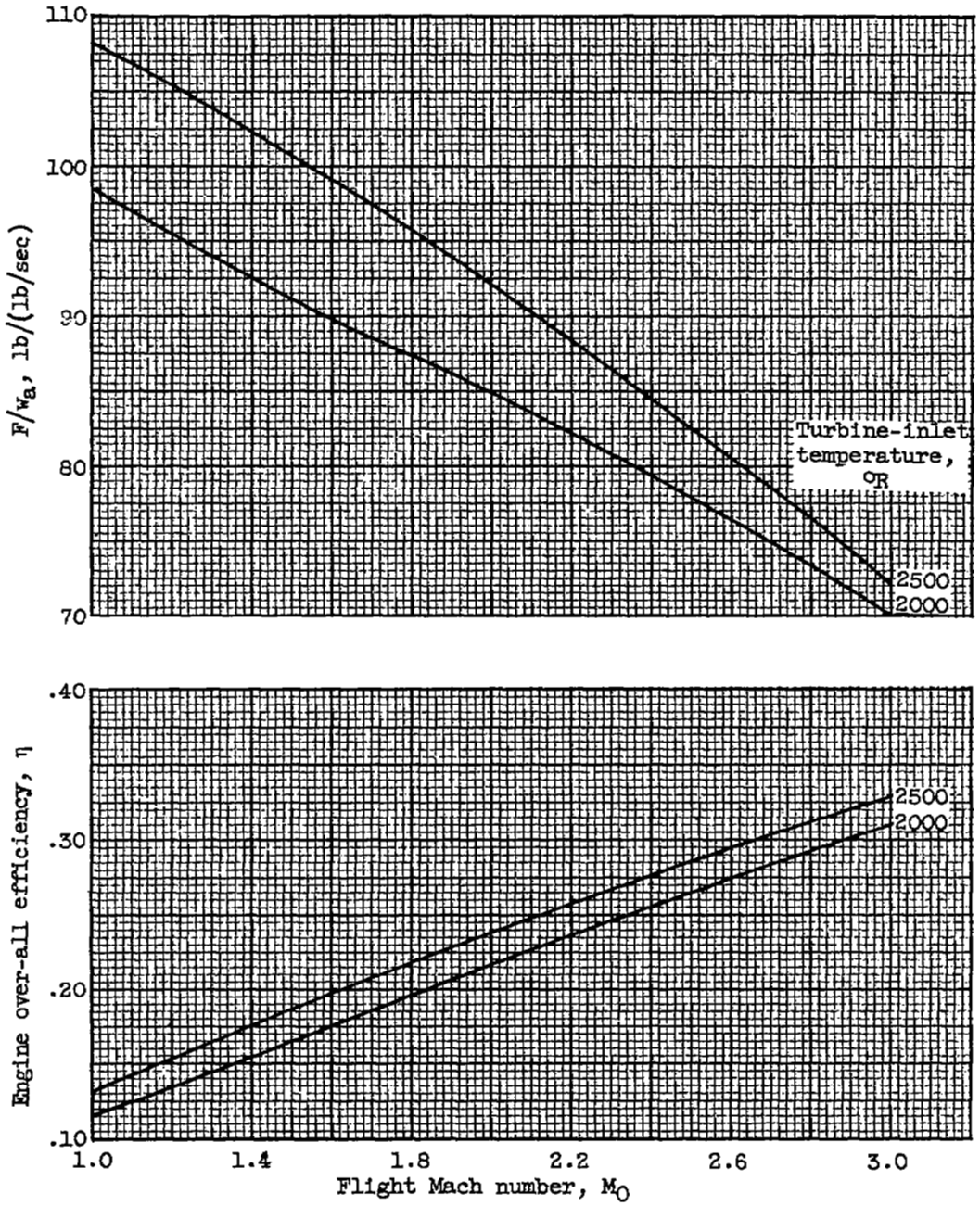
(b) Turbine-inlet temperature, 2500° R.

Figure 6. - Continued. Turbojet cycle performance with hydrogen fuel. Afterburner temperature, 3500° R.



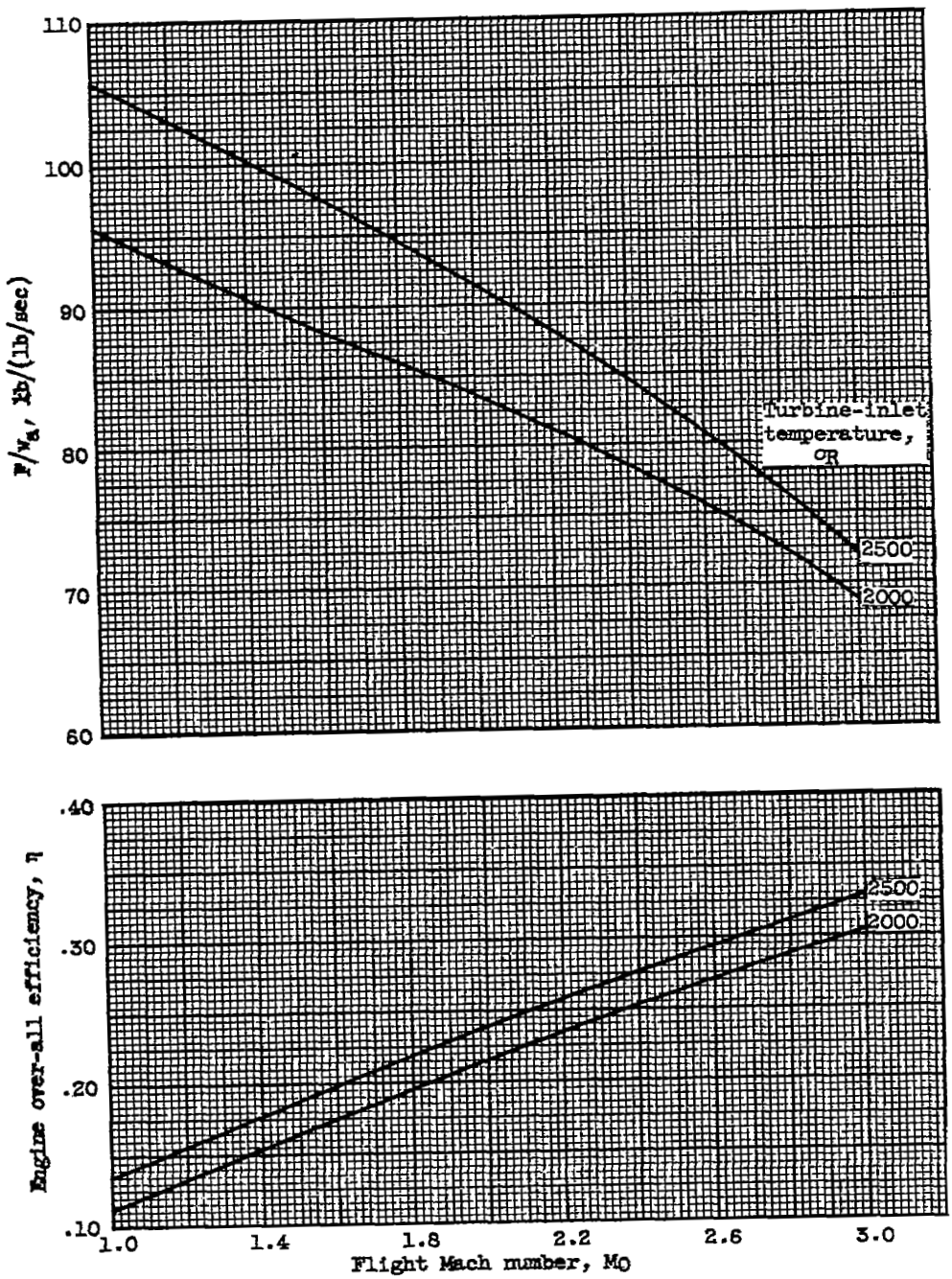
(c) Turbine-inlet temperature, 3000° R.

Figure 6. - Concluded. Turbojet cycle performance with hydrogen fuel. Afterburner temperature, 3500° R.



(a) Equilibrium expansion in exhaust nozzle.

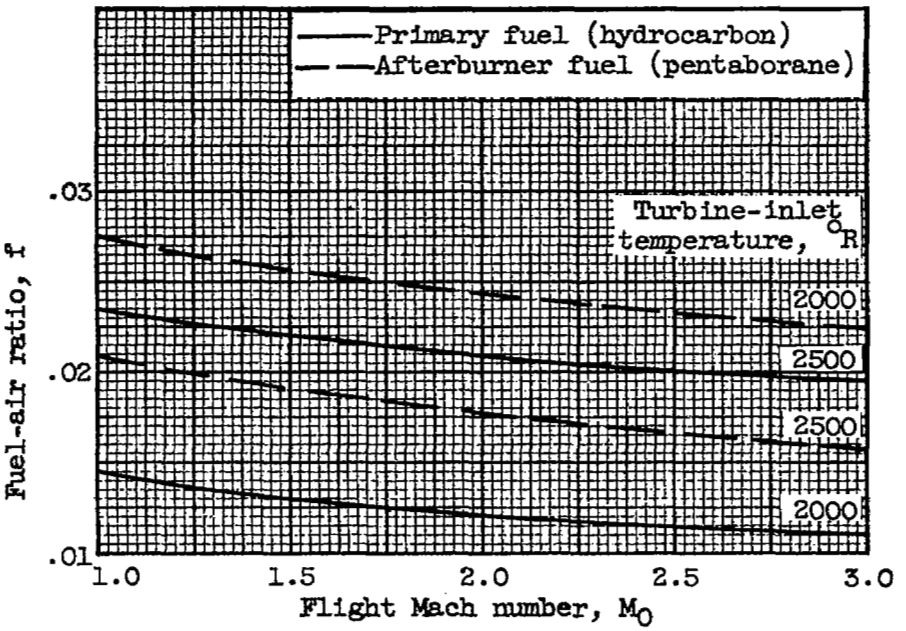
Figure 7. - Turbojet cycle performance with hydrocarbon fuel in primary combustor and pentaborane in afterburner. Rated compressor pressure ratio varied with flight Mach number; afterburner temperature, 3500° R; altitude, 40,000 feet.



(b) Frozen expansion in exhaust nozzle.

Figure 7. - Continued. Turbojet cycle performance with hydrocarbon fuel in primary combustor and pentaborane in afterburner. Rated compressor pressure ratio varied with flight Mach number; afterburner temperature, 3500° R; altitude, 40,000 feet.

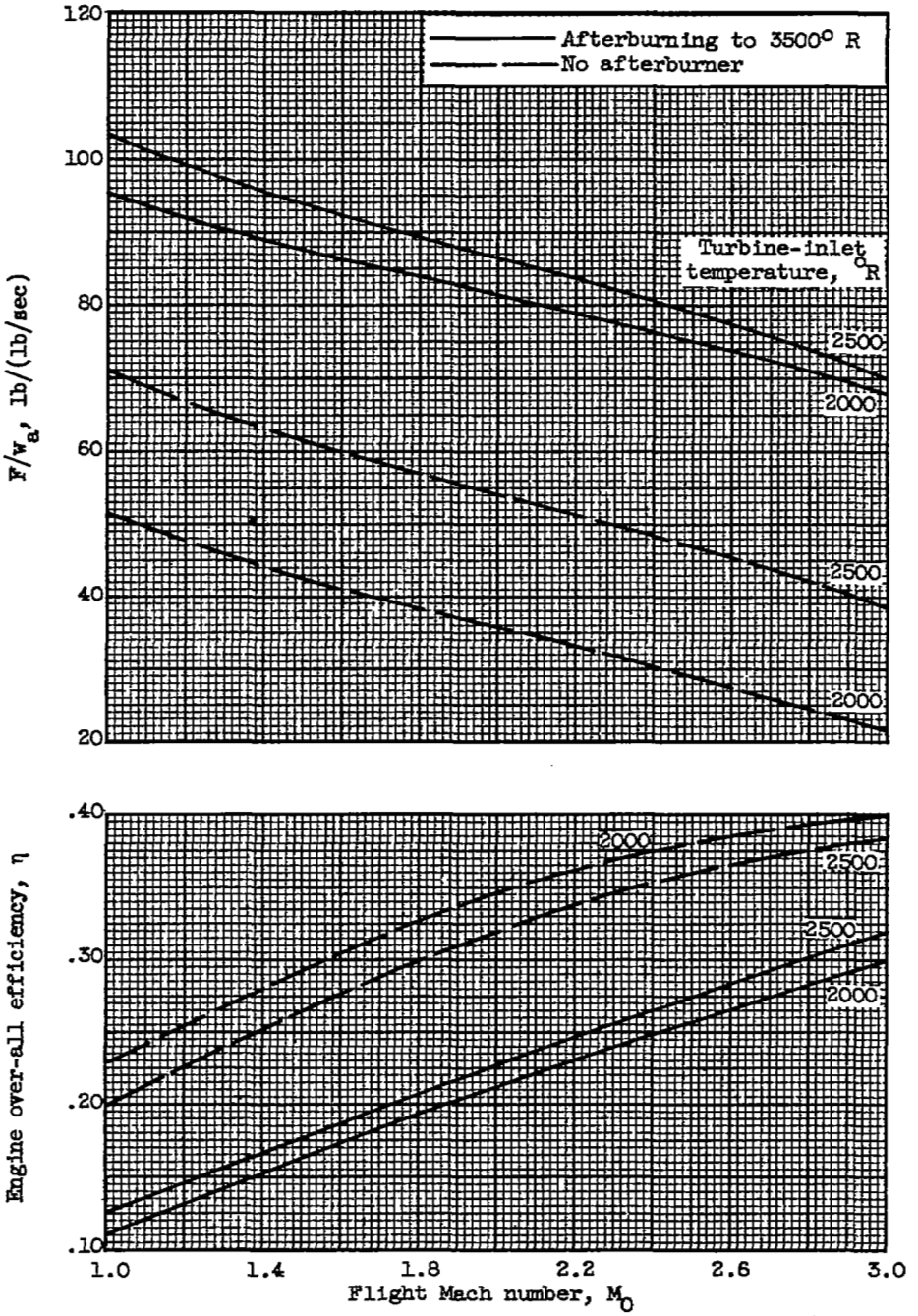
CJ-4



(c) Fuel-air ratios.

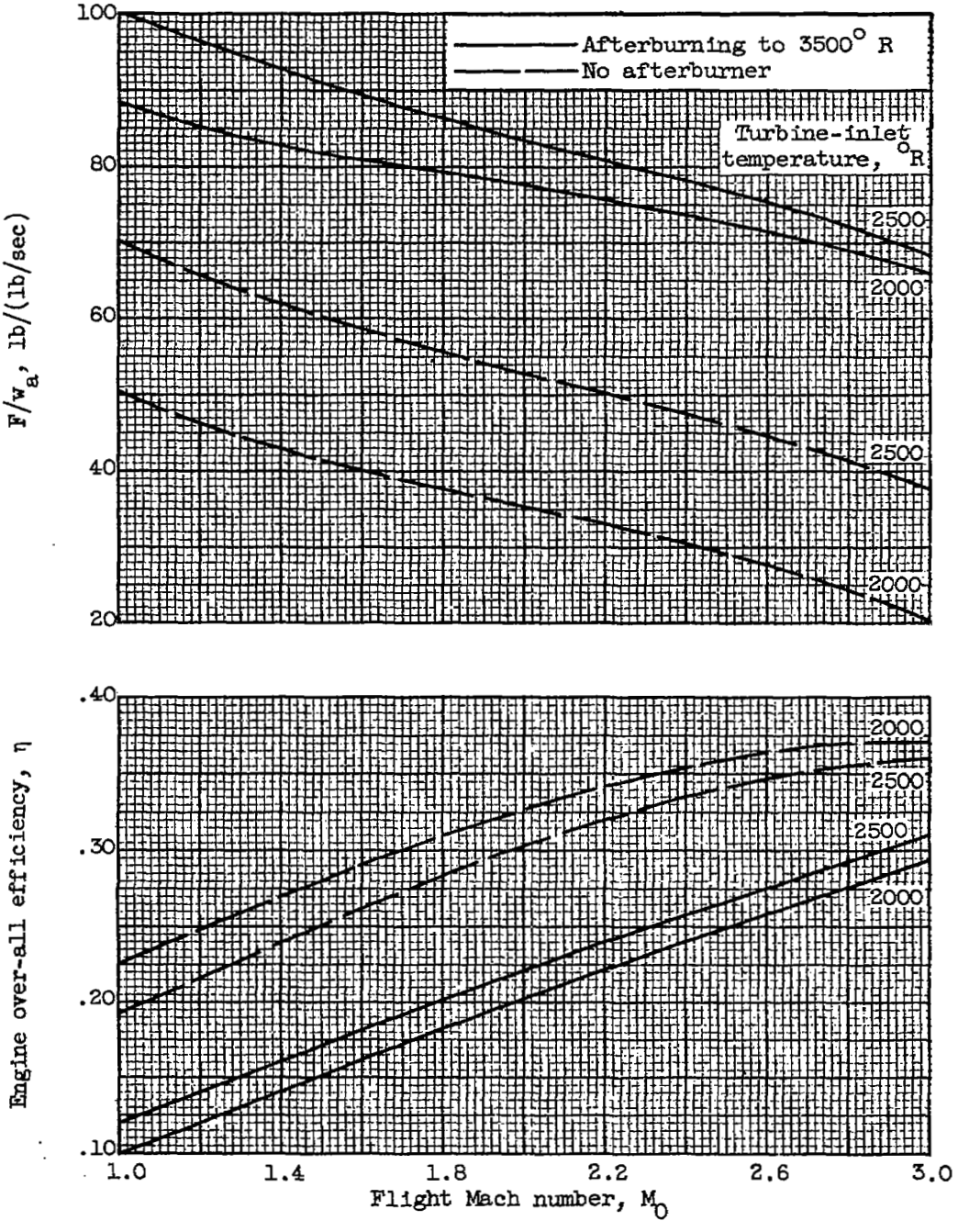
Figure 7. - Concluded. Turbojet cycle performance with hydrocarbon fuel in primary combustor and pentaborane in afterburner. Rated compressor pressure ratio varied with flight Mach number; afterburner temperature, 3500° R; altitude, 40,000 feet.

CJ-4 back



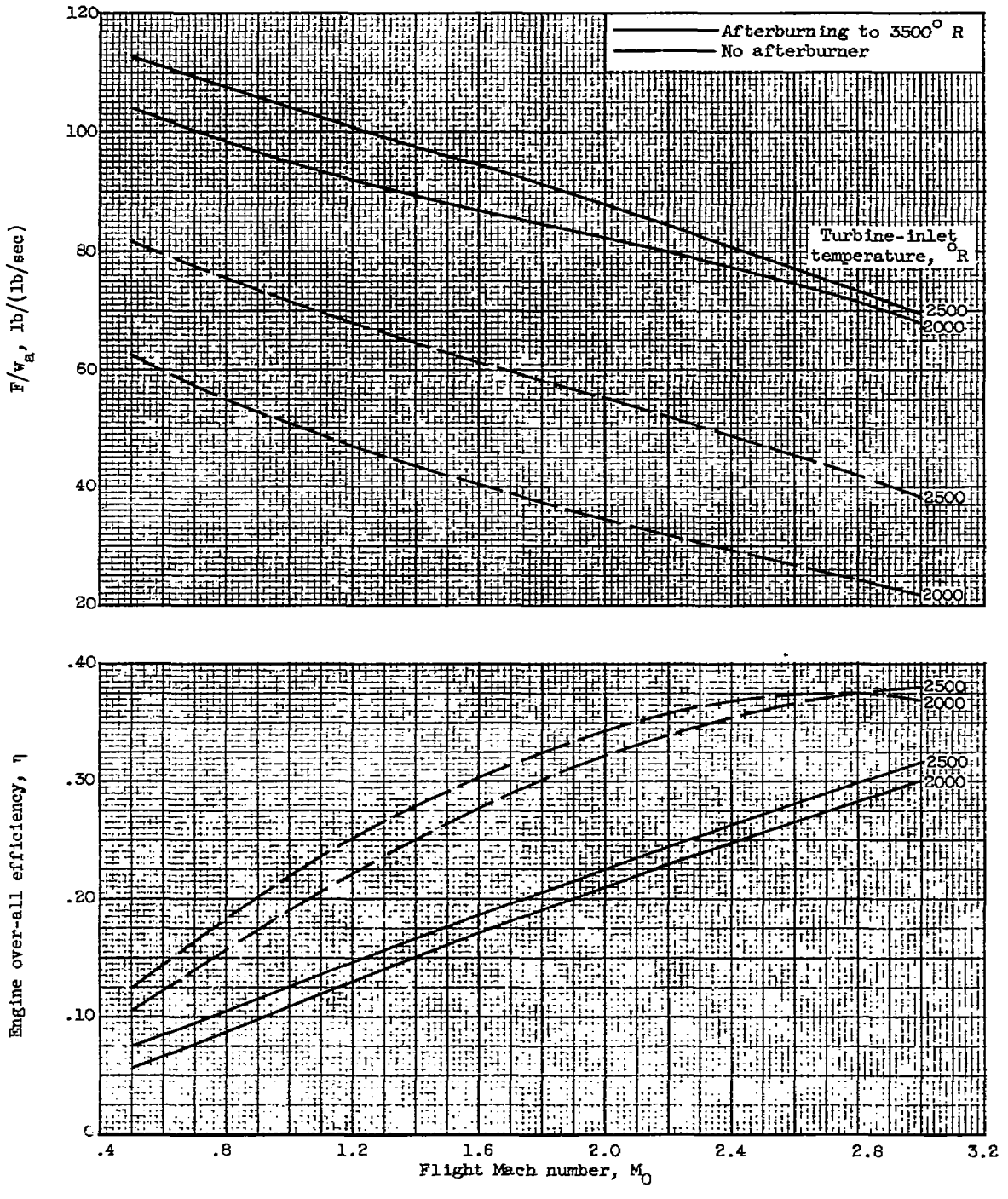
(a) Equilibrium expansion in exhaust nozzle.

Figure 8. - Turbojet cycle performance with pentaborane fuel. Rated compressor pressure ratio varied with Mach number; altitude, 40,000 feet.



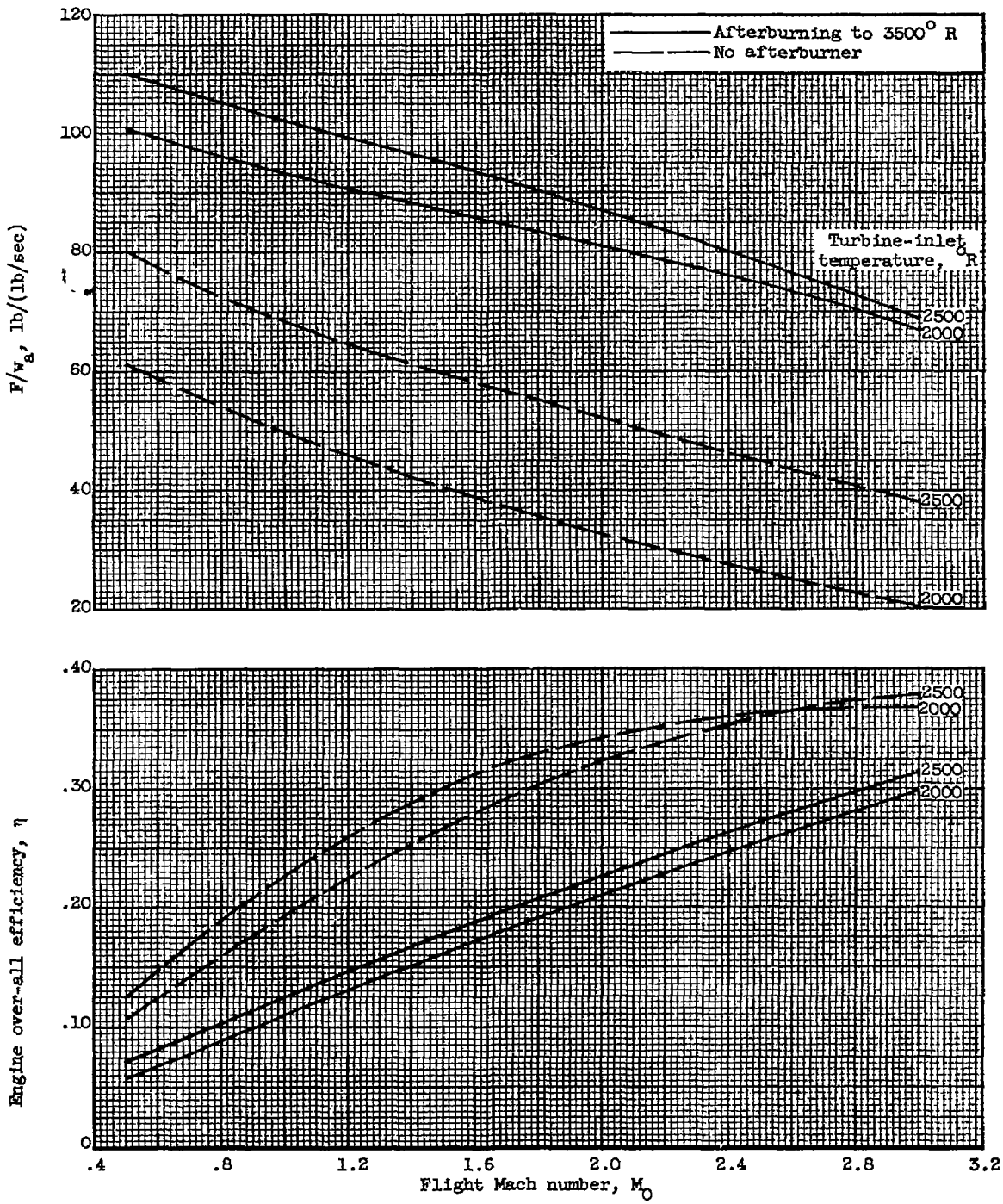
(b) Frozen expansion in exhaust nozzle.

Figure 8. - Concluded. Turbojet cycle performance with pentaborane fuel. Rated compressor pressure ratio varied with Mach number; altitude, 40,000 feet.



(a) Equilibrium expansion in exhaust nozzle.

Figure 9. - Turbojet cycle performance with ethylene decaborane fuel. Rated compressor pressure ratio varied with flight Mach number; altitude, 40,000 feet.



(b) Frozen expansion in exhaust nozzle.

Figure 9. - Concluded. Turbojet cycle performance with ethylene decaborane fuel. Rated compressor pressure ratio varied with flight Mach number; altitude, 40,000 feet.

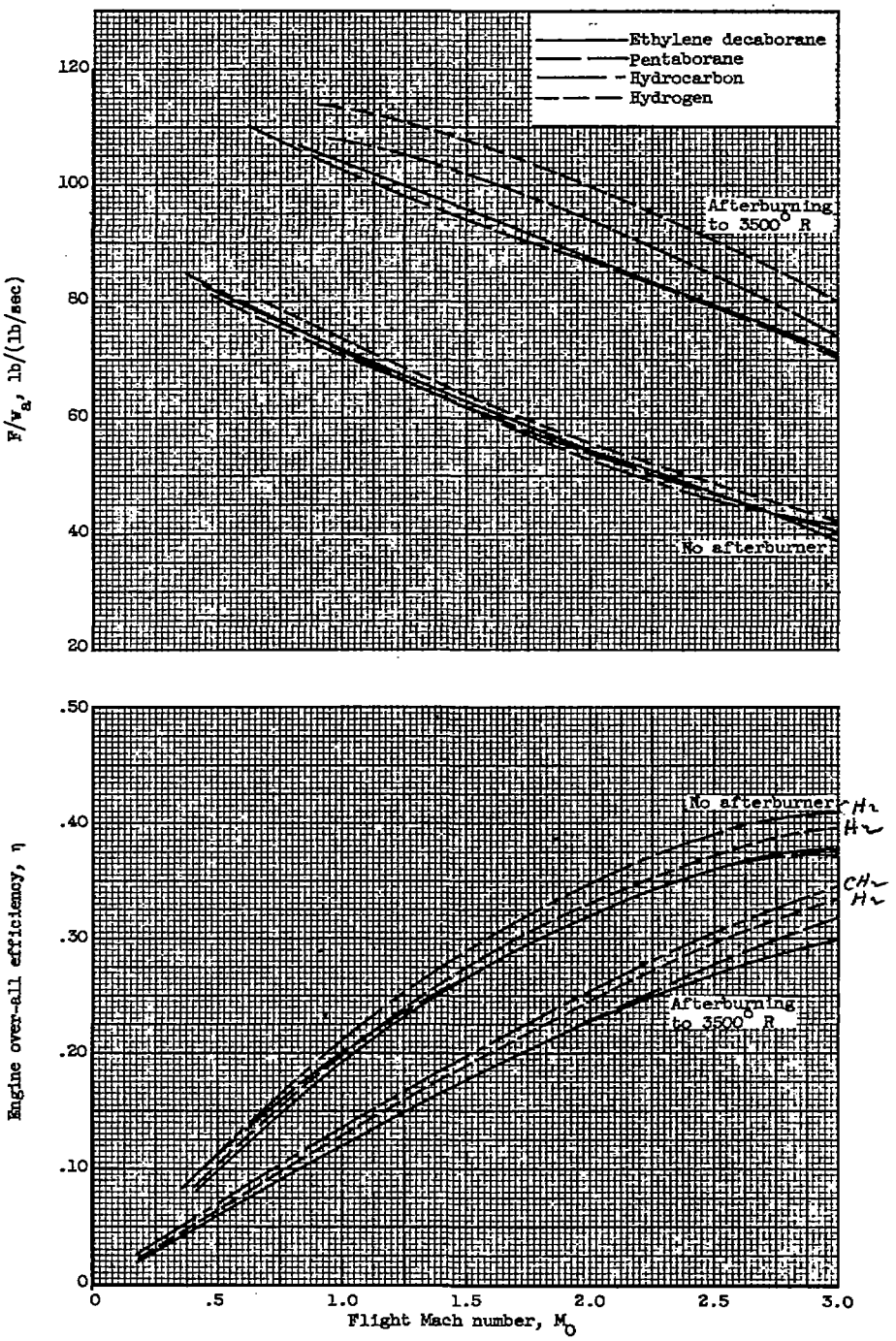
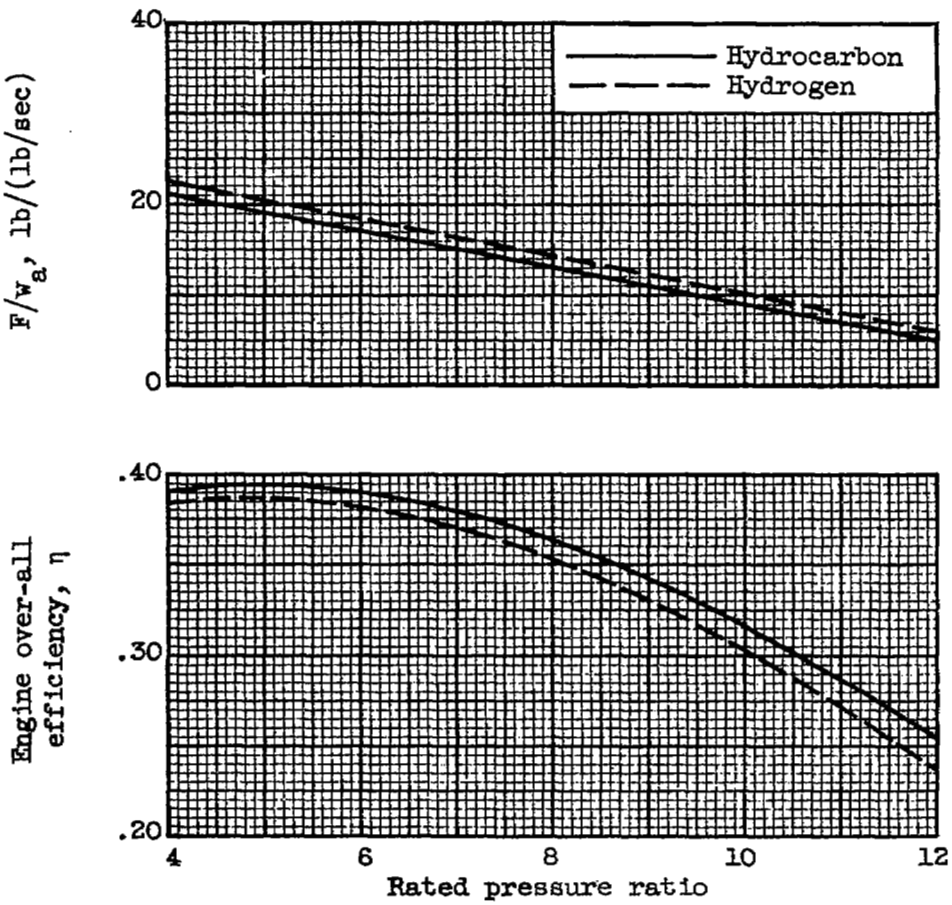


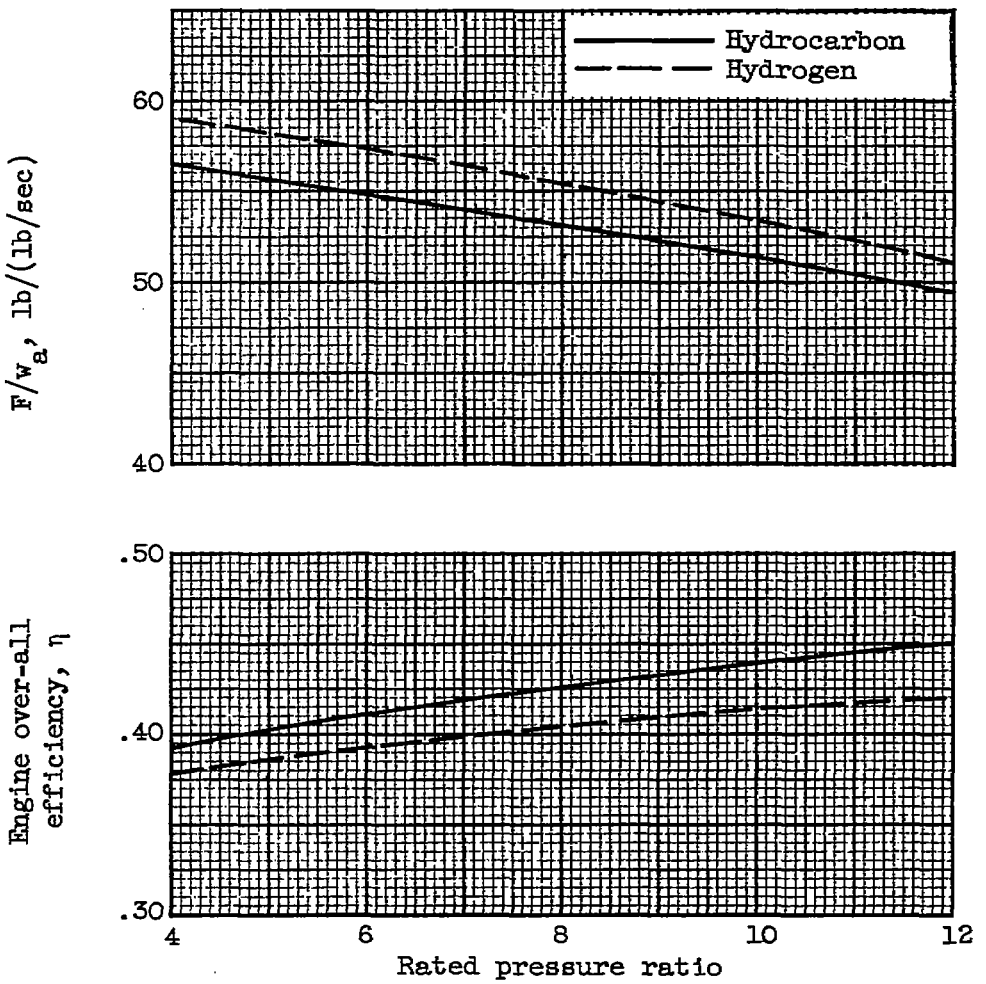
Figure 10. - Turbojet cycle performance with various fuels. Rated compressor pressure ratio varied with flight Mach number; turbine-inlet temperature, 2500° R; equilibrium expansion in exhaust nozzle; altitude, 40,000, feet.

[redacted]



(a) Turbine-inlet temperature, 2000° R; no afterburner.

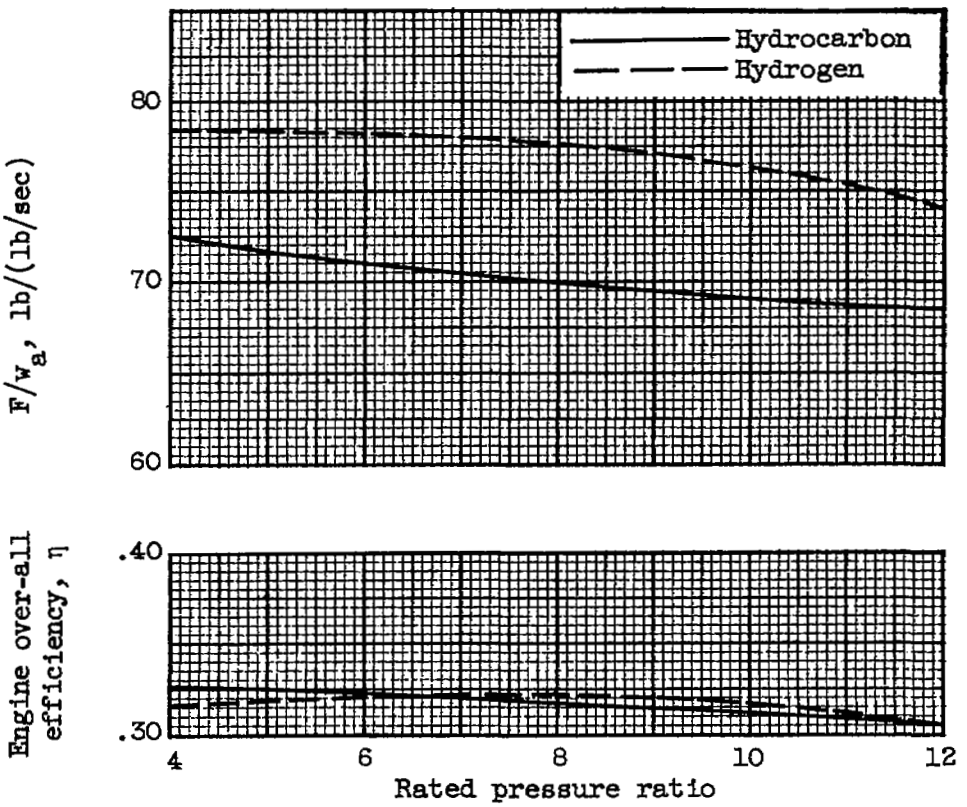
Figure 11. - Effect of rated compressor pressure ratio on turbojet cycle performance. Flight Mach number, 3.0.



(b) Turbine-inlet temperature, 3000° R; no afterburner.

Figure 11. - Continued. Effect of rated compressor pressure ratio on turbojet cycle performance. Flight Mach number, 3.0.

CJ-5



(c) Turbine-inlet temperature, 2000° R; afterburning to 3500° R.

Figure 11. - Concluded. Effect of rated compressor pressure ratio on turbojet cycle performance. Flight Mach number, 3.0.

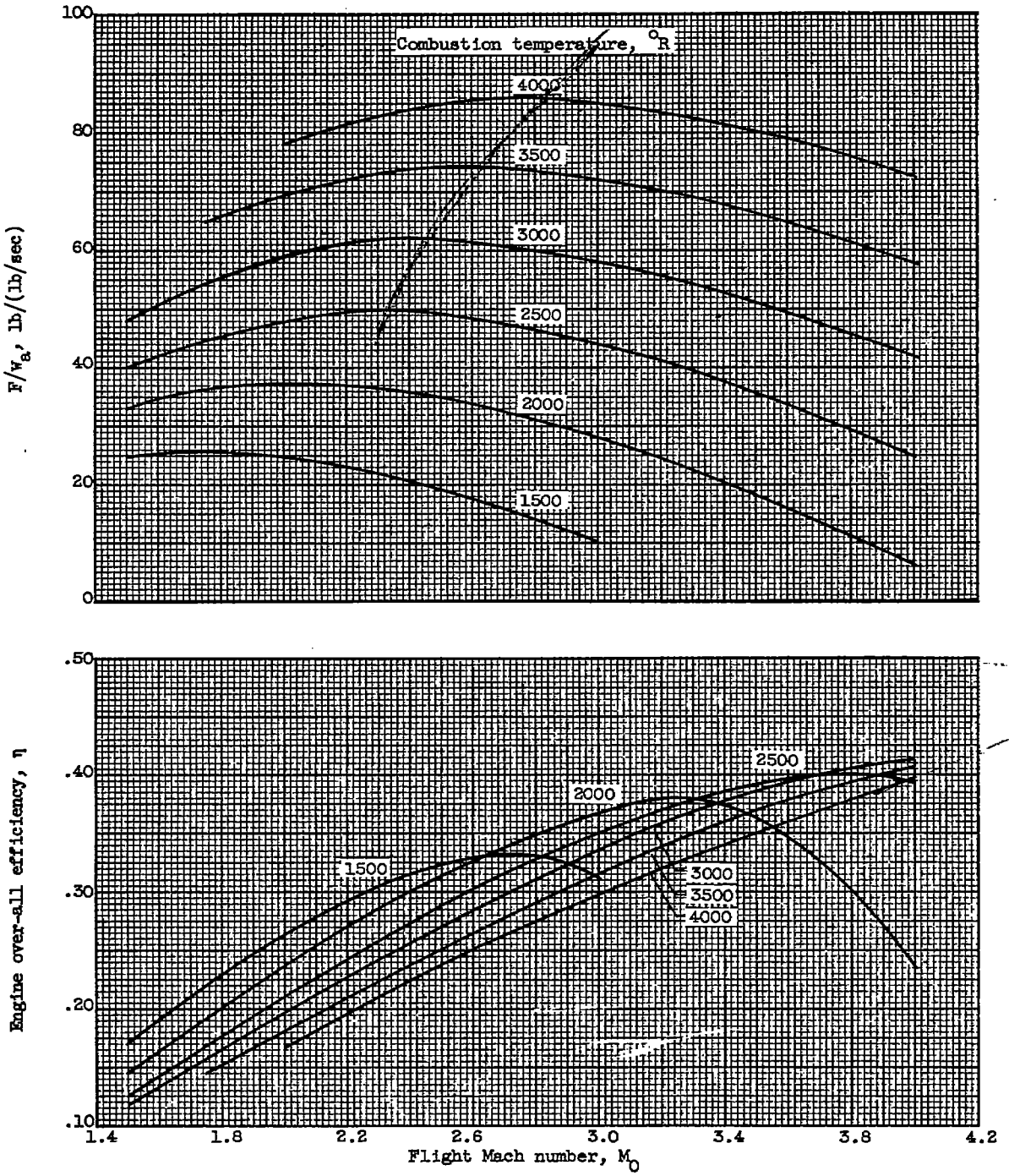


Figure 12. - Ram-jet cycle performance with hydrocarbon fuel.

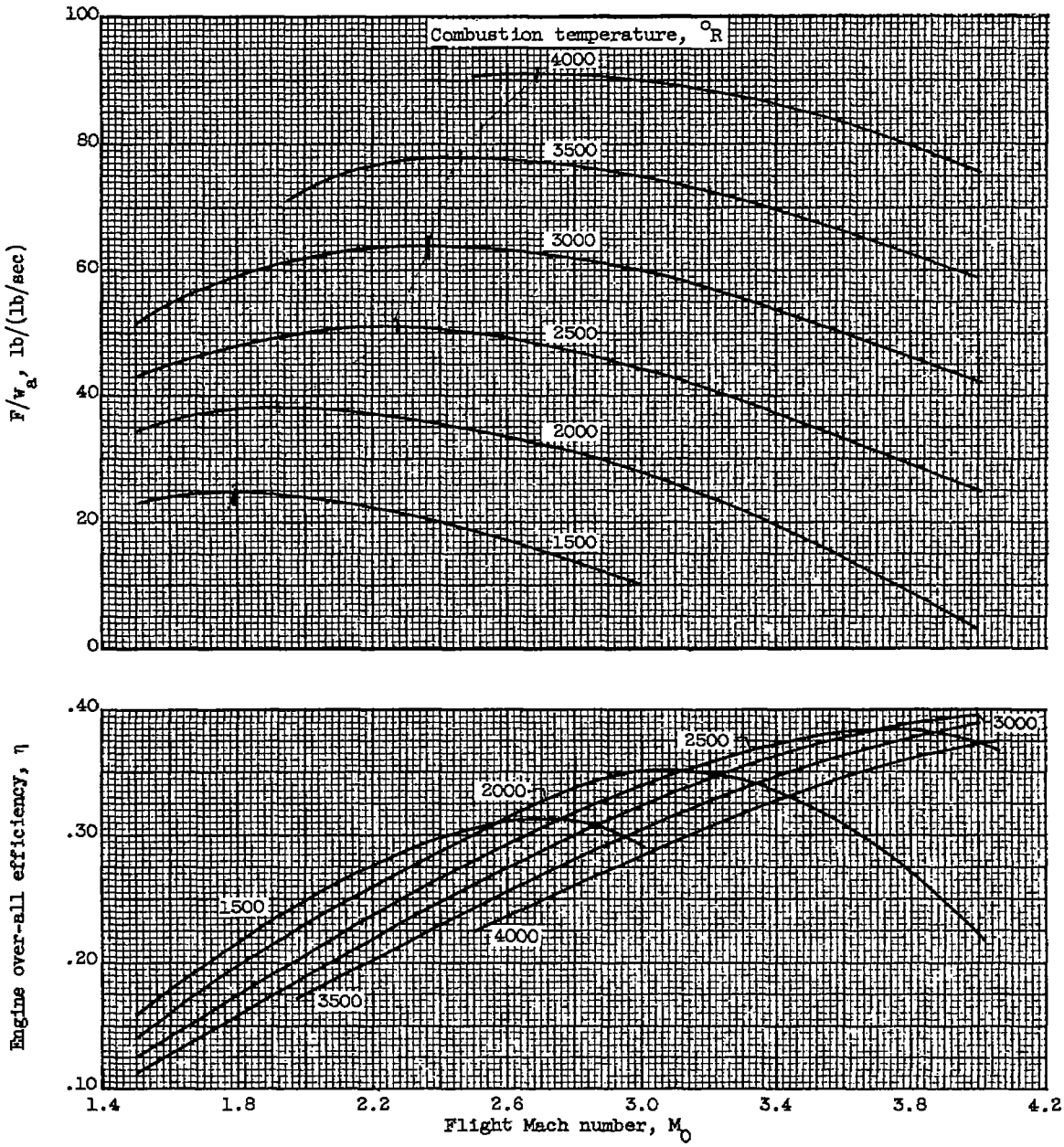
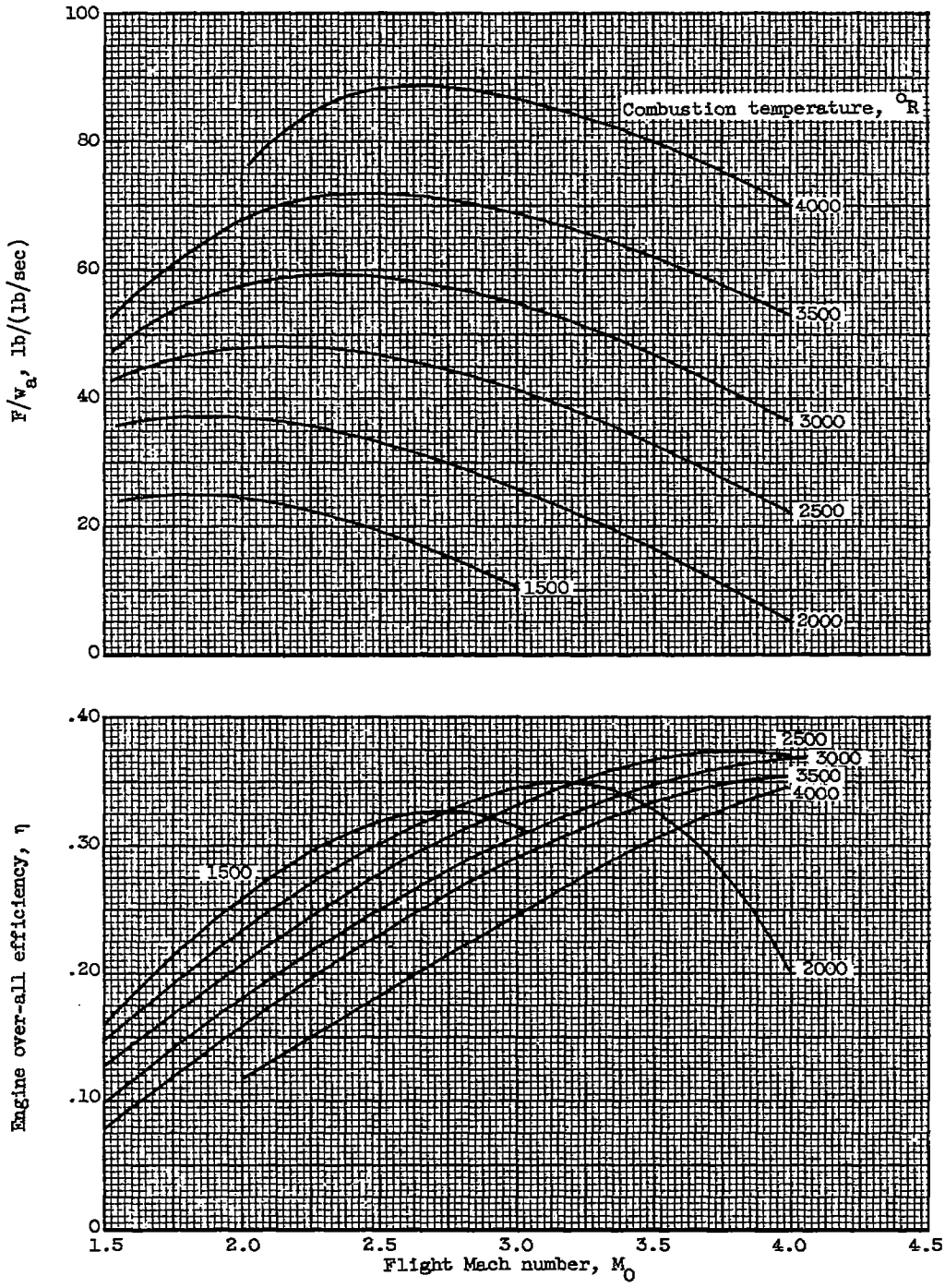
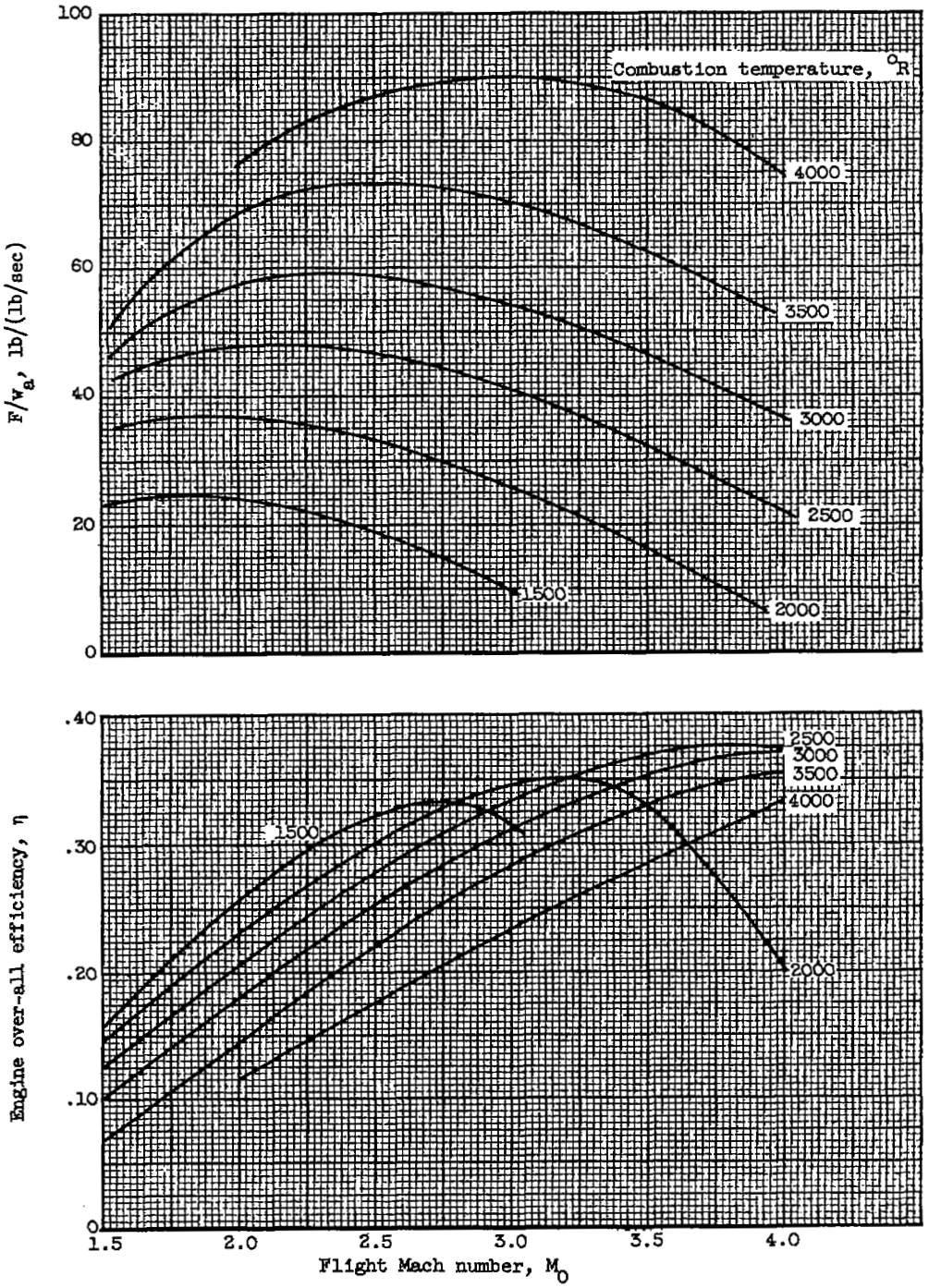


Figure 13. - Ram-jet cycle performance with hydrogen fuel.



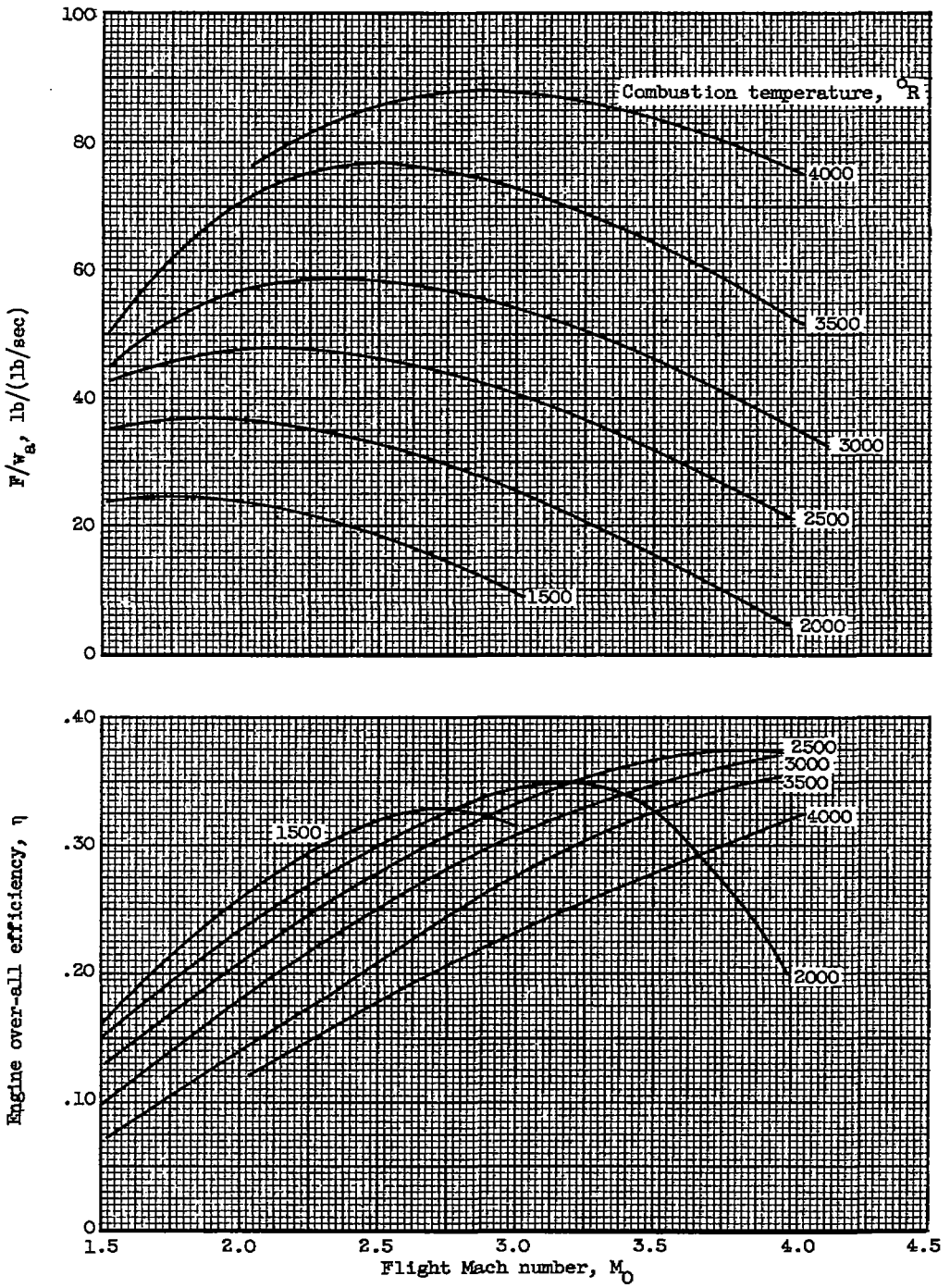
(a) Altitude, 40,000 feet.

Figure 14. - Ram-jet cycle performance with pentaborane fuel. Equilibrium expansion in exhaust nozzle.



(b) Altitude, 60,000 feet.

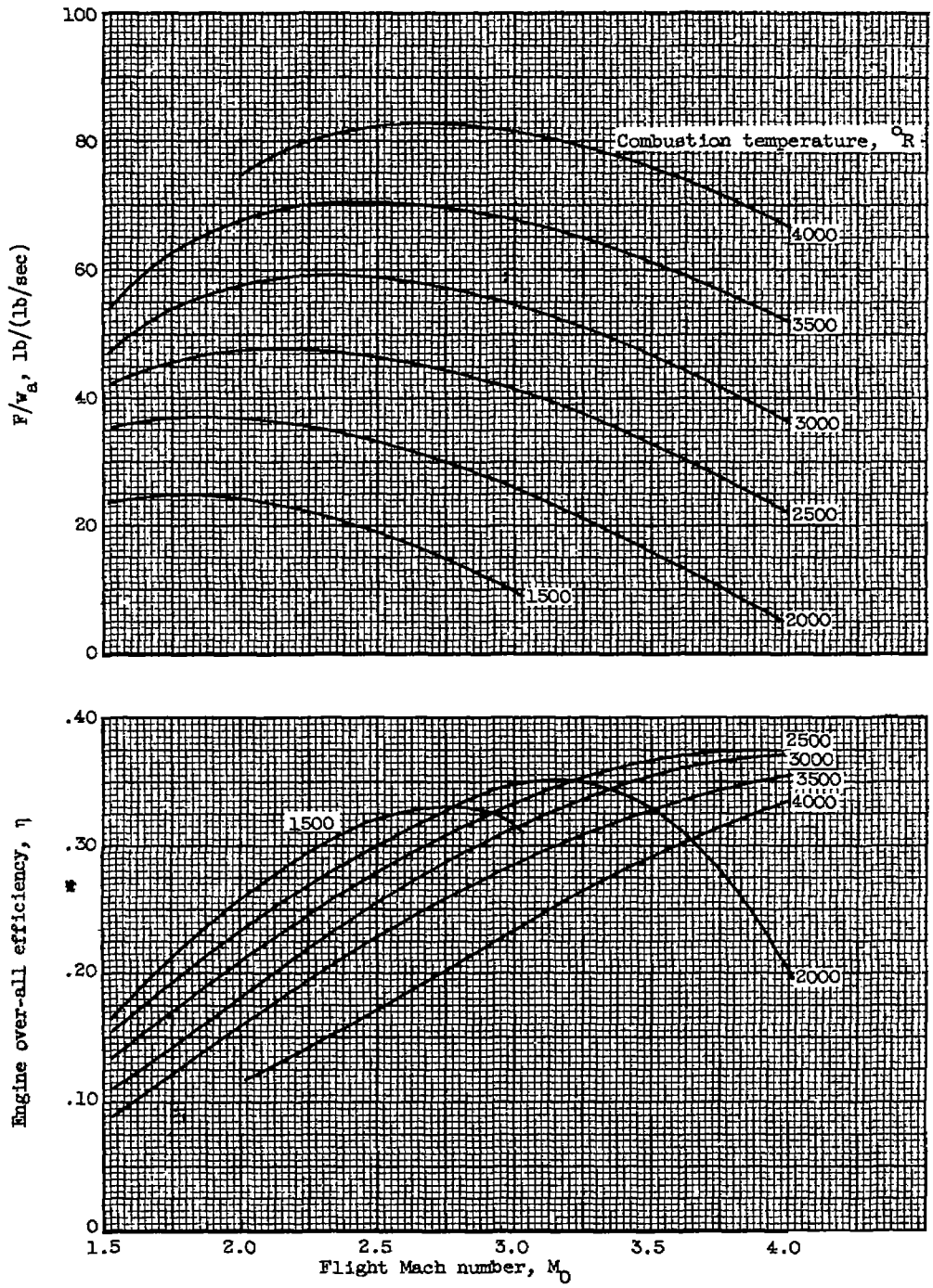
Figure 14. - Continued. Ram-jet cycle performance with pentaborane fuel. Equilibrium expansion in exhaust nozzle.



(c) Altitude, 80,000 feet.

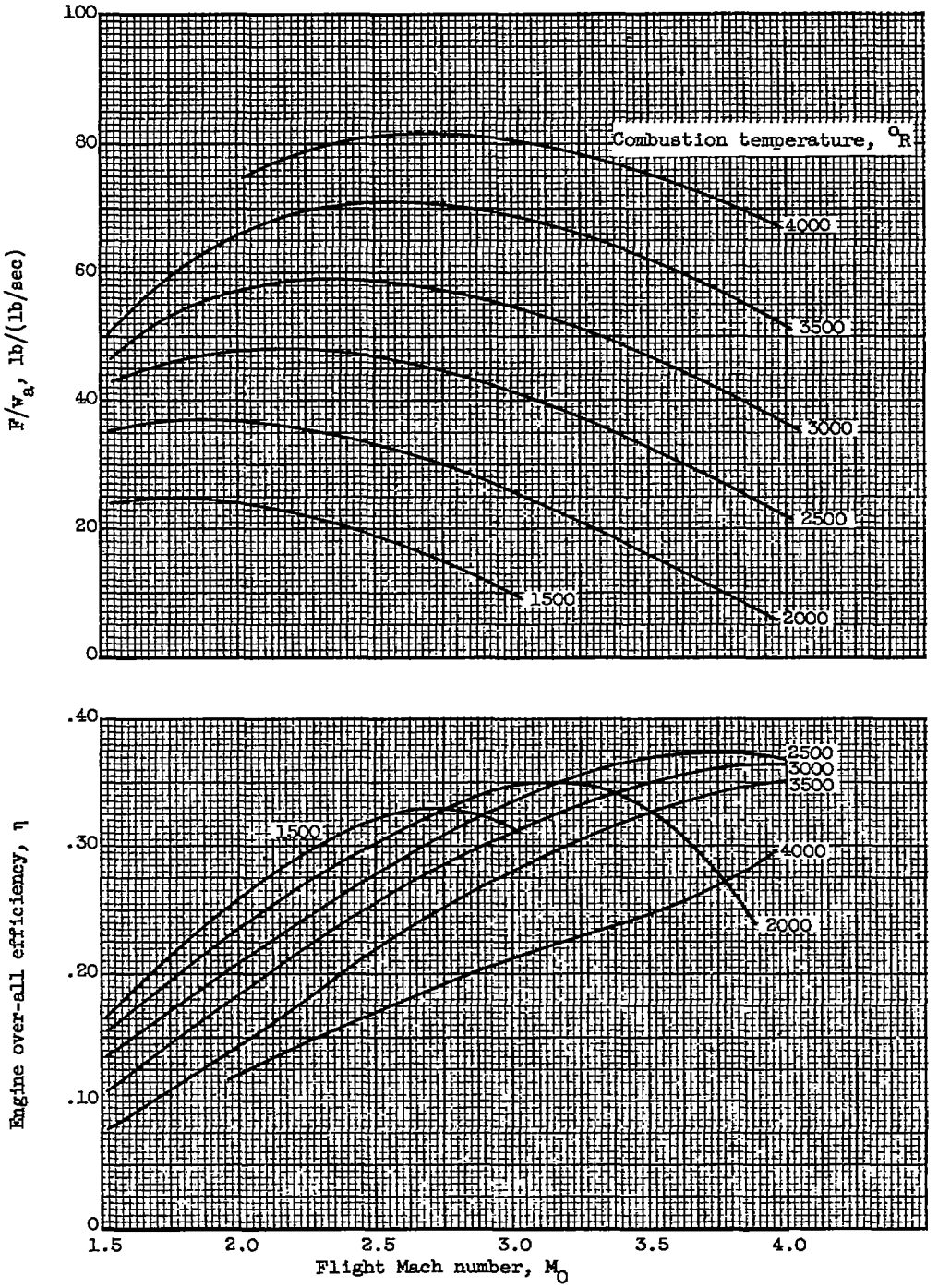
Figure 14. - Concluded. Ram-jet cycle performance with pentaborane fuel. Equilibrium expansion in exhaust nozzle.

[redacted]



(a) Altitude, 40,000 feet.

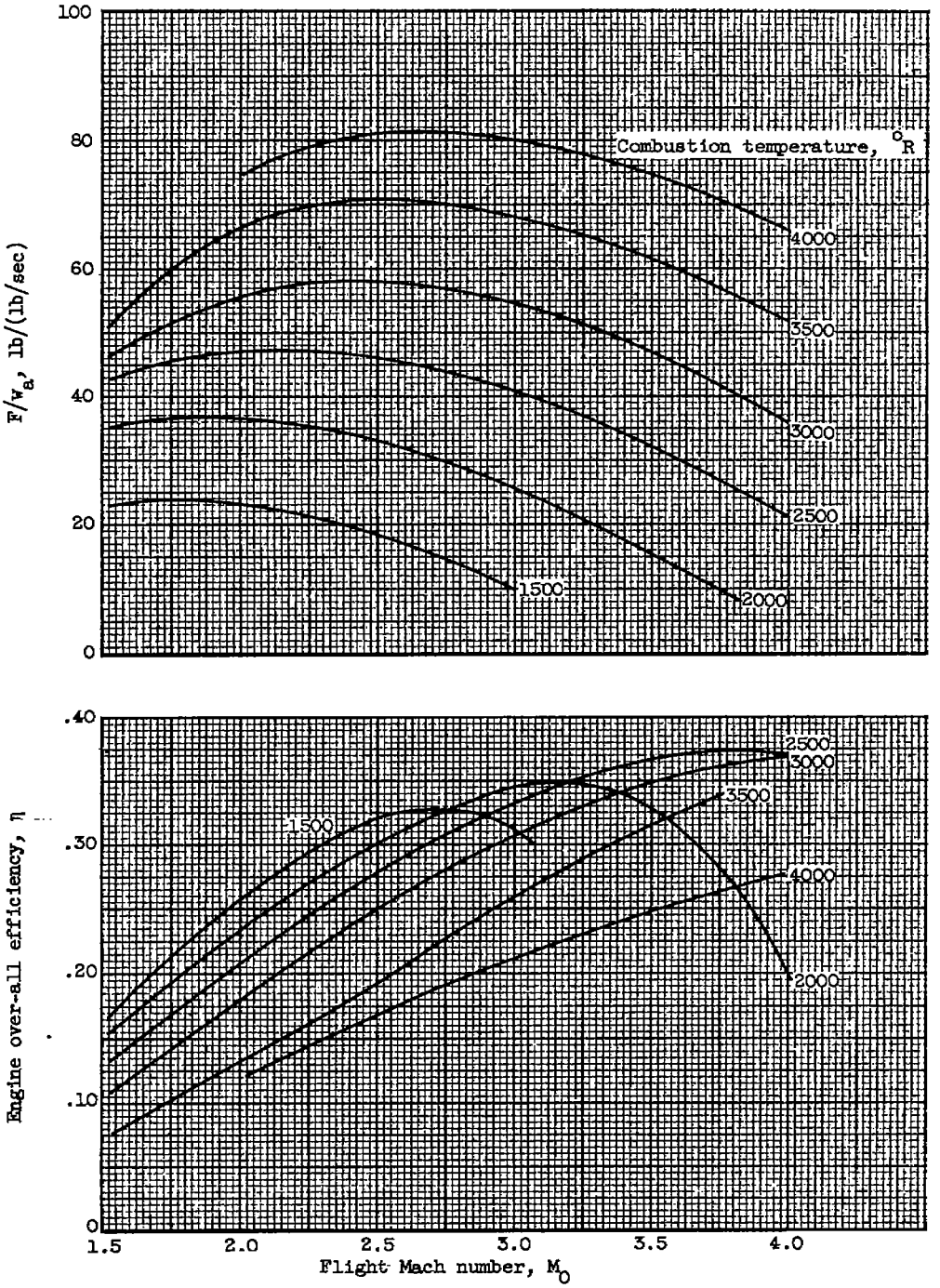
Figure 15. - Ram-jet cycle performance with pentaborane fuel. Frozen expansion in exhaust nozzle.



(b) Altitude, 60,000 feet.

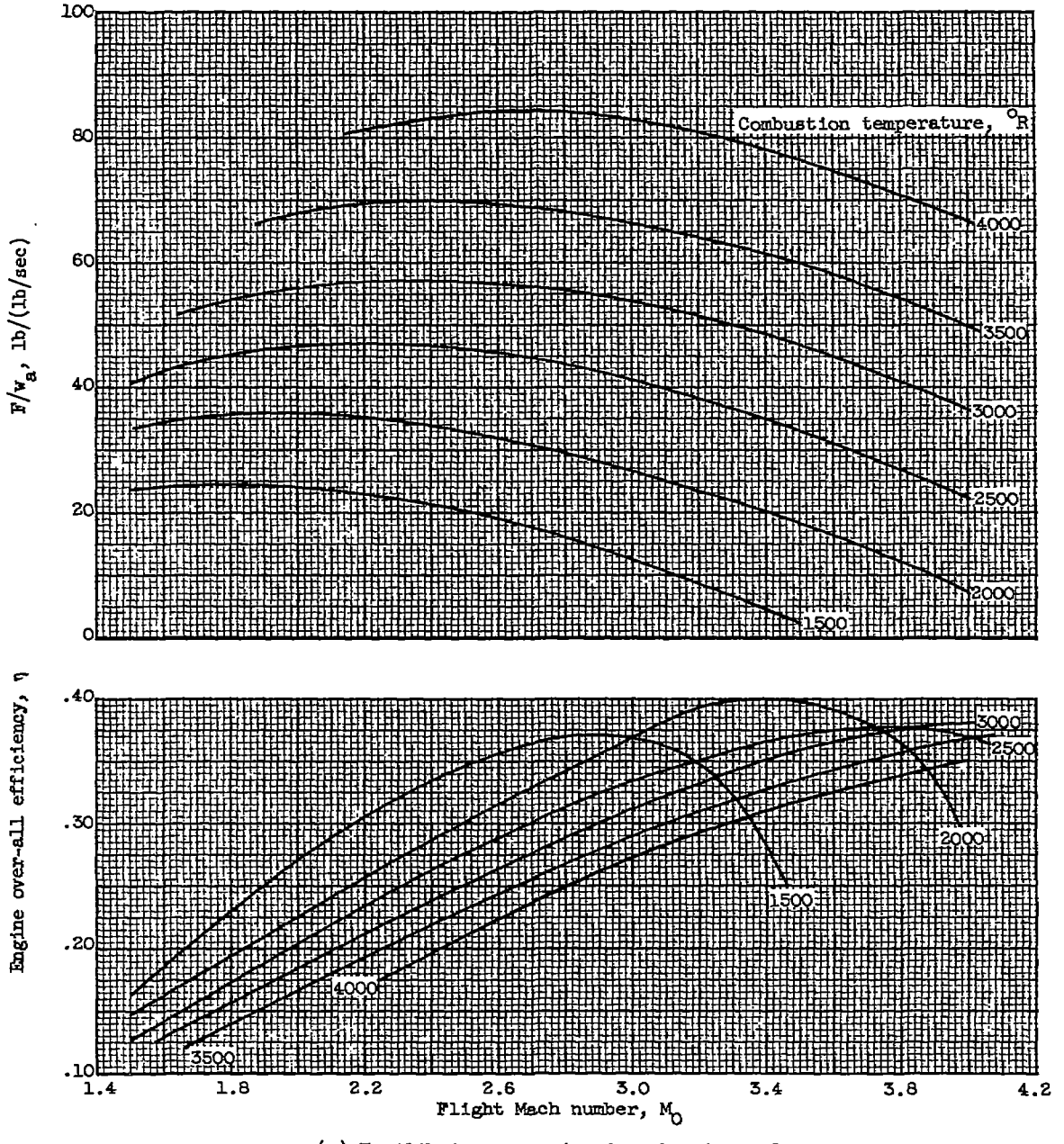
Figure 15. - Continued. Ram-jet cycle performance with pentaborane fuel. Frozen expansion in exhaust nozzle.

CJ-6



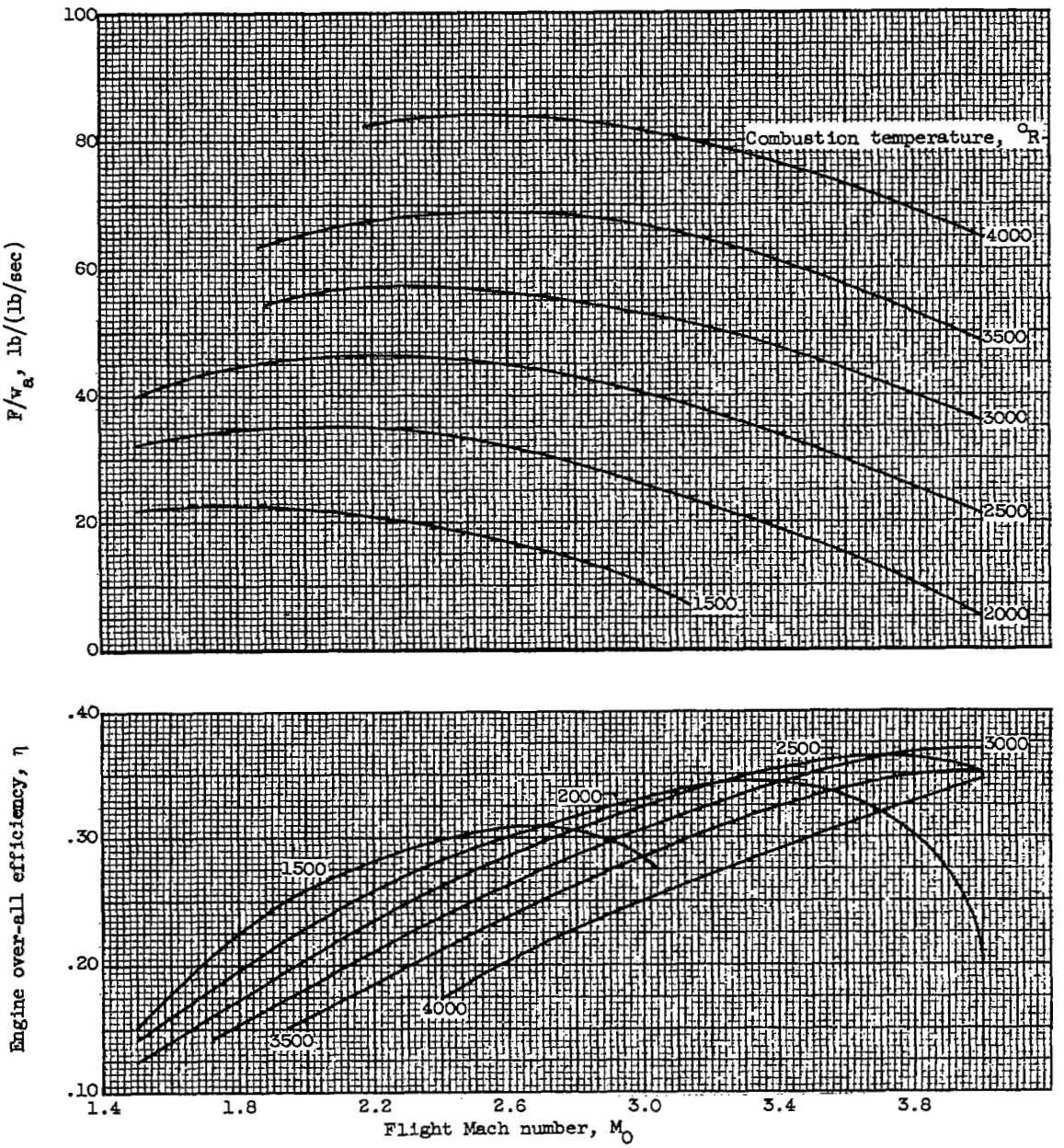
(c) Altitude, 80,000 feet.

Figure 15. - Concluded. Ram-jet cycle performance with pentaborane fuel. Frozen expansion in exhaust nozzle.



(a) Equilibrium expansion in exhaust nozzle.

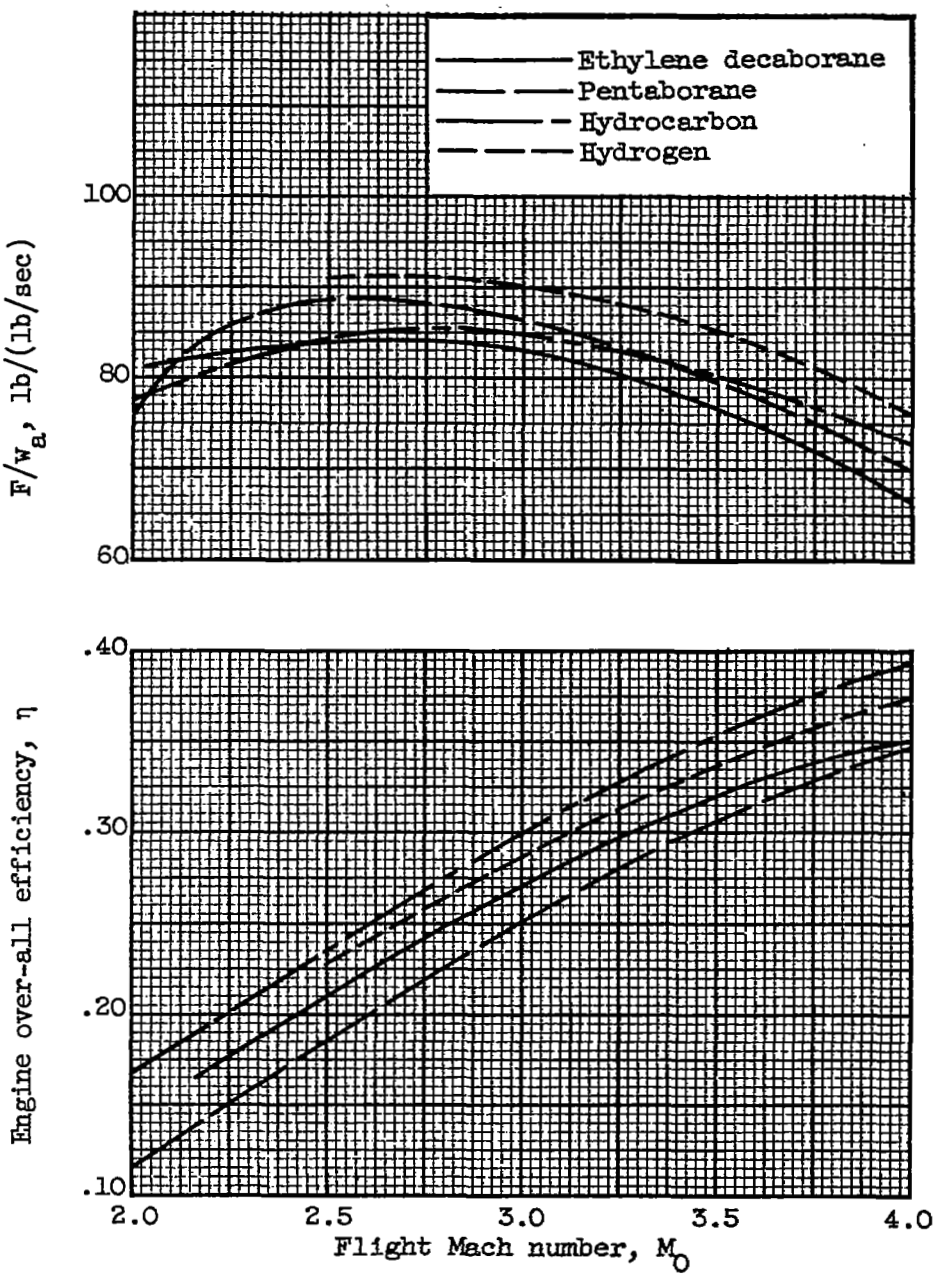
Figure 16. - Ram-jet cycle performance with ethylene decaborane fuel. Altitude, 40,000 feet.



(b) Frozen expansion in exhaust nozzle.

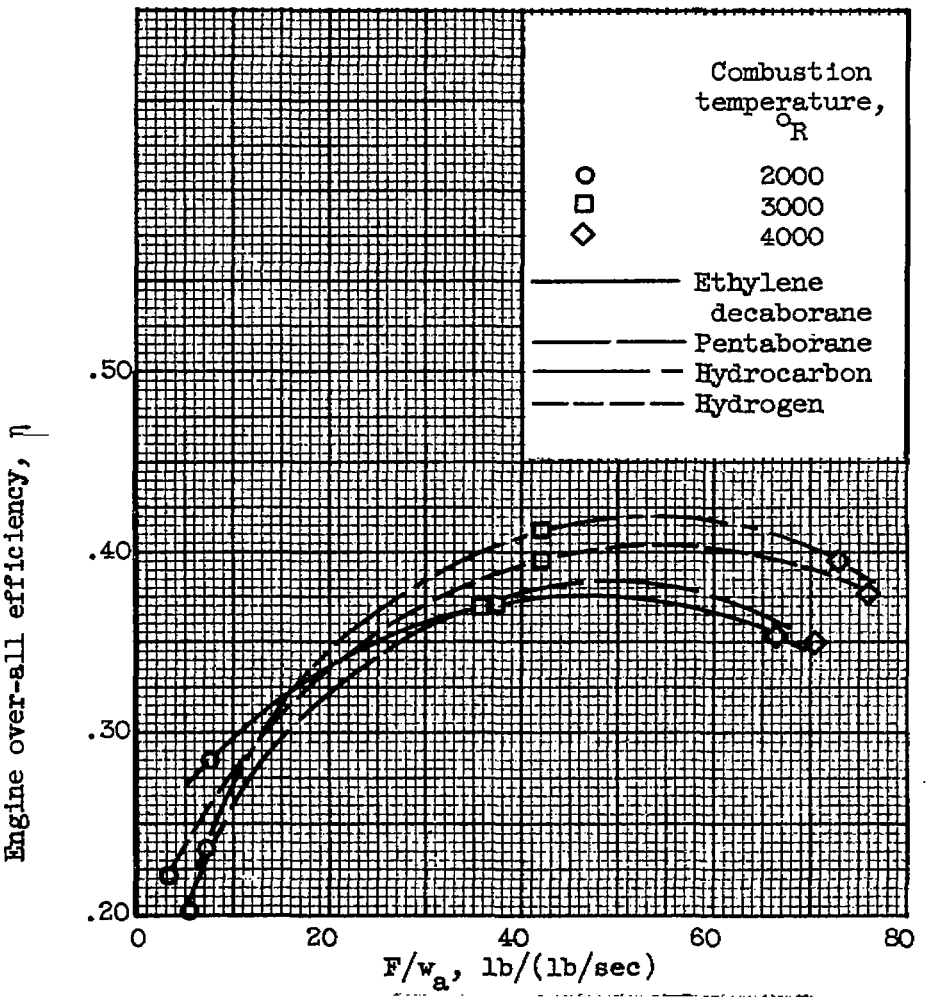
Figure 16. - Concluded. Ram-jet cycle performance with ethylene decaborane fuel. Altitude, 40,000 feet.

[redacted]



(a) Combustion temperature, 4000° R.

Figure 17. - Ram-jet cycle performance with various fuels. Equilibrium expansion in exhaust nozzle; altitude, 40,000 feet.



(b) Flight Mach number, 4.0.

Figure 17. - Concluded. Ram-jet cycle performance with various fuels. Equilibrium expansion in exhaust nozzle; altitude, 40,000 feet.

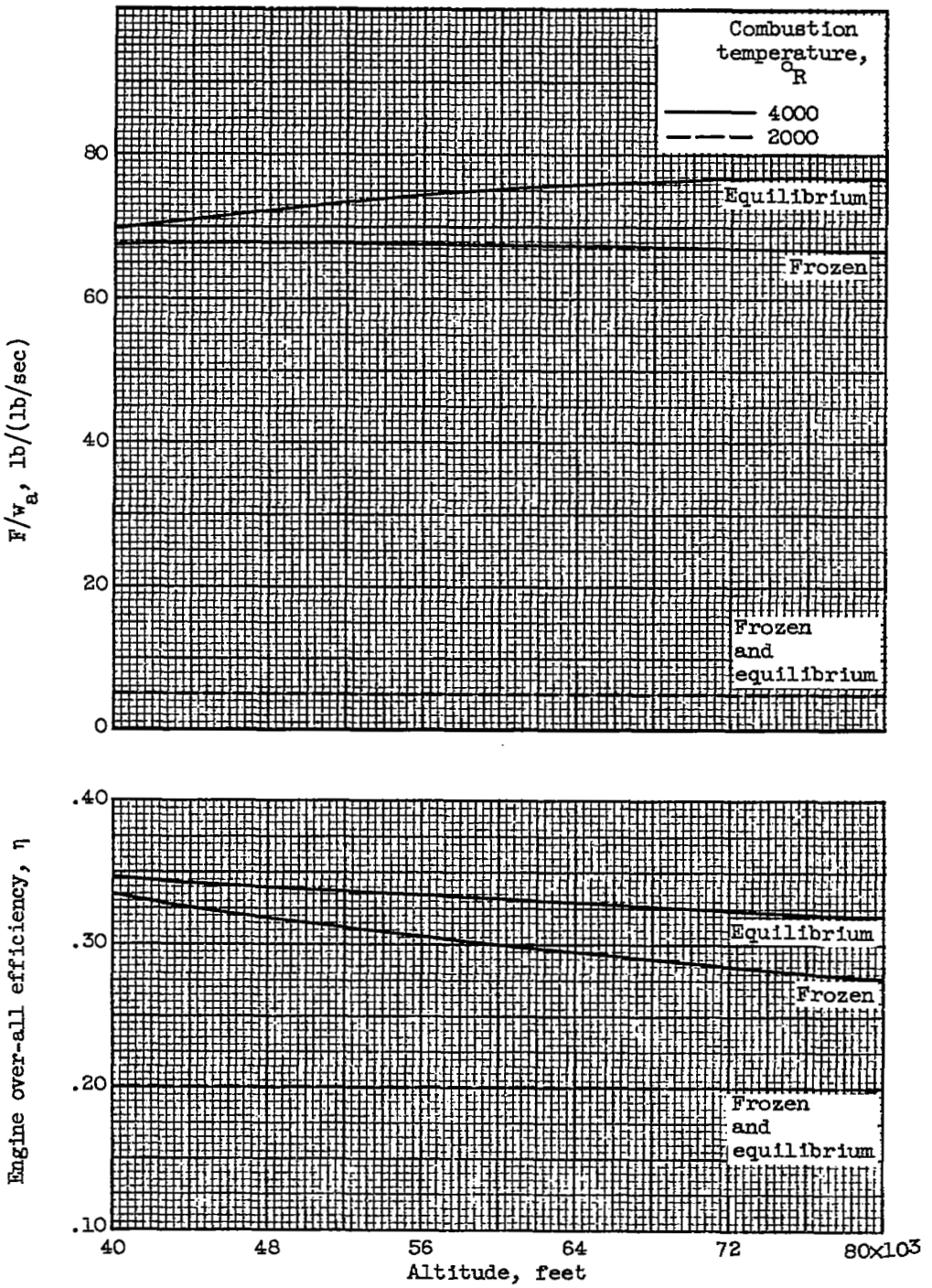


Figure 18. - Effect of altitude on ram-jet cycle performance with pentaborane fuel. Flight Mach number, 4.0.

[redacted]